Color Superconductivity in Neutron Stars

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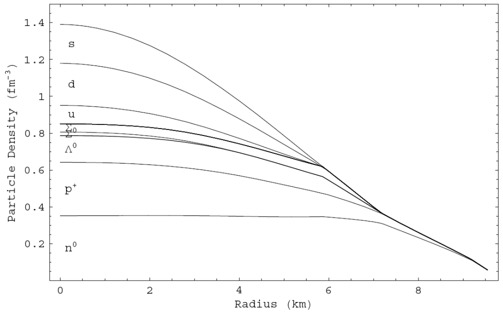
Superconducting quarks

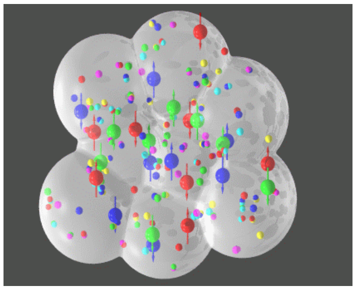
Density profile of a maximum mass neutron star (1.48 solar mass):



Typical neutron star temperature $\sim 10^8$ K
Quark Fermi temperature $\sim 10^{13}$ K

Deconfined Quarks

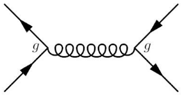
A deconfined phase of quarks, called the quark-gluon plasma, might be possible at the core of a maximum mass neutron star (see figure). Due to the large Fermi temperature this degenerate gas of quarks is effectively at zero temperature and can become a superconductor by forming Cooper pairs.



Quark-gluon plasma

The 2SC phase

At the densities relevant to neutron stars only the lightest quarks (up, down, strange) become deconfined. In the so-called 2SC phase we only consider pairs of up and down quarks with different color, flavor and spin. The reason is that the interaction between quarks, which is described by one-gluon exchange,



is attractive when the quarks have different colors. Furthermore, we assume that the spinless condensate has the lowest energy such that we have singlet pairs. Consequently, the quarks must also have different flavors due to the Pauli principle. Note that in neutron stars we are dealing with an imbalanced Fermi gas, since the densities of the (u,d) quarks are unequal at the core.

The order parameter of the 2SC phase:

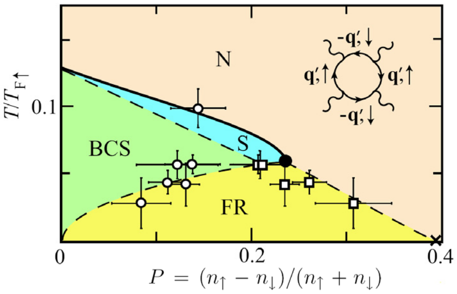
the BCS gap

$$\langle\psi\psi\rangle = \begin{array}{cccccccc} & \text{up} & \text{down} & \text{up} & \text{down} & \text{up} & \text{down} & \\ \left(\right. & 0 & 1 & & & & \emptyset & \left.\right) \text{up} \\ & 1 & 0 & & & & & \text{down} \\ & & & 0 & -1 & & & \text{up} \\ & & & -1 & 0 & & & \text{down} \\ & & & & & 0 & 0 & \text{up} \\ & \emptyset & & & & 0 & 0 & \text{down} \end{array} \times (C\gamma_5) \times \Delta(p)$$

Spin singlet

Imbalanced Fermi gases

Phase diagram of a spin-imbalanced atomic gas [2]:



N: Normal phase
S: Sarma phase (similar to 2SC phase)
BCS: Superconducting phase (Bose-condensed Cooper pairs)
FR: Forbidden Region (phase separation)

The Sarma and the 2SC phase

The Sarma phase, known from experiments on spin-imbalanced atomic gases, has been shown to be equal to the 2SC phase. Thus, in future research, we would like to use the theoretical framework of [2] to map the transition of the quark-gluon plasma to the 2SC phase and determine the possible tricritical point.

Shown here is the phase diagram of a spin-imbalanced atomic gas containing the known experimental data, the Renormalization Group (RG) calculation of [2] (solid black line) and the tricritical point (black dot).

References:
[1] J.M. Diederix – Color Superconductivity in Neutron Stars, Master's thesis (http://www1.phys.uu.nl/wwwitf/Teaching/2007/Diederix.pdf)
[2] K.B. Gubbels, H.T.C. Stoof – Renormalization Group Theory for the Imbalanced Fermi Gas (arXiv: cond-mat/0711.2963)
[3] S. Scherer – Figure of Quark-Gluon Plasma (http://th.physik.uni-frankfurt.de/~scherer)
Further Reading: M.G. Alford, A. Schmitt, K. Rajagopal, T. Shäfer – Color superconductivity in dense quark matter (arXiv:0709.4635v2)