Physics 569 Term paper
Color Flavor Locked Quark matter properties

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December 15, 2011

Abstract

Quark matter at its highest densities; is expected to become a color superconductor and transition to a phase called color flavor locking (CFL)[1]. Because of asymptotic freedom, the theory becomes weaker at high densities [1] and some kind of superconductivity can be expected[2]. At the CFL phase it behaves as a superfluid[3]and has Chiral Symmetry breaking[1]. Possible observations or experimental evidence such as measurements of temperature and energy of neutron stars may give information about the interior[4], also gravity wave detection may give information about the density of the stars[5].

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1 Introduction

In the following literature review, the phenomenon of Color Flavor Locking (CFL) will be introduced, along with its properties. CFL is a phase of quark matter which results due to the breaking of several symmetries of Quantum Chromodynamics (QCD). An interesting property of CFL is Color Superconductivity which is the QCD analog to the one that occurs in metal due to Cooper pairing of electrons. Experiments, which will be discussed, have been proposed to verify these predictions made by QCD.

2 Color Flavor Locked Quark matter

2.1 Color SuperConductivity

Quantum Chromodynamics (QCD) was confirmed experimentally after perturbative calculations based on asymptotic freedom. This behavior of a wide class of non-abelian gauge theories was first explained by Gross, Wilczek and Politzer in 1973[6]. It wasn't long after this when it was proposed that a phase transition from the hadron confined phase of quark matter could emerge a neutron-quark phase at densities of about ten to twenty times the nuclear matter density, say inside of a neutron star.[7]

Following the prediction of this neutron-quark state, its properties started to be analyzed. Since quarks are spin-1/2 fermions, due to their asymptotic freedom behavior, at high densities some sort of cooper pairing might be expected, this following assumptions done by Bardeen, Cooper and Schriepper[2]. This behavior was first proposed by Barrois in 1977 [8].

Barrois argued that due to the asymptotic freedom of QCD in dense quark matter the color force causes a superconductivity-like phenomenon. At sufficient high density, the quarks form a degenerate fermi liquid. The quarks that are near the fermi surface of this degenerate fermi liquid, will of course have a weak binding because of weak QCD interactions and so will be almost free. Thus the argument goes just as in[2]: At T=0 (high density, low T limit), the

Free energy is,

$$F = E - \mu N$$

We know that the chemical potential μ for a degenerate fermi liquid must be equal to the fermi energy E_F given that there are no interactions, so that at the Fermi surface adding or getting rid of a quark costs zero energy. Therefore the energy will be lowered given that quark-hole pair is created in the fermi sea. Thus, it would be energetically favored for these Cooper pairs to be created. And since they are bosonic in nature, due to their spin configuration, they will form a condensate.

In QCD superconductivity arises due to the antisymmetry of the Wavefunction for the strong interaction at high momentum transfer, or the "Coulomb" part of the interaction. This then is a consequence of the primary interaction, which in turn has interesting consequences[1]. Due to the asymptotic behavior, a gap parameter can be derived from the microscopic theory [1] just like in [2]. Also, at densities where the interaction becomes stronger the ratio of the gap parameter Δ to the fermi energy E_F is greater than in the BCS theory for superconducting materials. This differentiates color superconductivity from the original superconducting theory. In QCD color singlets cannot exist and, unlike in BCS theory, the Cooper pairs will have to break the local color (gauge) symmetry $SU(3)_c$[1]. Thus, color superconductivity is a consequence of spontaneous symmetry breaking.

Quantum Chromodynamics asymptotic freedom best predictions are due to asymptotic freedom, therefore quark matter with the highest densities is likely to be well predictable by QCD (See fig. 1). The Color Flavor Locked (CFL) phase is an emerging phenomena well explained at these scales.

2.2 Color Flavor Locked Quark matter

At really high densities flavor distinction is neglected and the most favored phase is the one in which quarks of all three colors and flavors couple with each other to form zero momentum spinless Cooper pairs[9]. It was shown in [9] and by 't Hooft that that these theories exibit spontaneous breaking at least some of the chiral flavor sym-

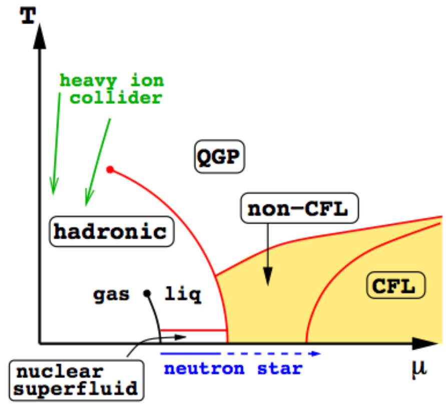

Figure 1: (Taken from [1]) Different phases of quark matter, QGP on top is the Quark Gluon Plasma phase.

metry. As summarized in [1] and developed in [9], the symmetry breaking pattern is,

$$SU(3)_c \times U_B(1) \times SU(3)_R \times SU(3)_L \to SU(3)_{c+L+R} \times \mathbb{Z}_2$$

where the $SU(3)_L$, $SU(3)_L$ are the chiral flavor symmetries. Associated to this symmetry breaking are some Goldstone modes, these elementary excitations (Goldstone bosons) form an octet in the mentioned representation of the group $SU(3)_{c+L+R}$. These Goldstone bosons are massive in nature due to the Higgs mechanism involved in the spontaneous symmetry breaking.

Furthermore, the baryon number symmetry $U_B(1)$ is also broken leaving behind the discrete symmetry $\mathbb{Z}_2$. $U_B(1)$ symmetry breaking implies the creation of massless Nambu Goldstone bosons correspond modes created. To this symmetry there is an associated order parameter[1], which has the structure of the expectation value of two Λ baryons, which are a particular linear combination of three quarks. The order parameter looks like,

$$\phi = \langle \Lambda\Lambda \rangle$$

As explained in [10] this is the order parameter of a superfluid, and can be studied from the perspective of Ginzburg-Landau theory.

Under rotations the CFL phase forms vortices as superfluid He^3 does but expels a fraction of external magnetic fields via Meisser effect.

3 Possible Experiments and Measurements

In the following section we discuss possible experimental evidence that could be probed using different methods, which will be of astrophysical nature.

3.1 Neutron Stars

Some compact stars might be "hybrid stars" a term meaning that they contain a quark core[11]. These stars have been predicted to have a mass to radius relationship similar to that of nucleic matter. Masses go up to $2M_\odot$ in this model. The hybrid stars are likely candidates for the study of these exciting phenomena. Even though there is no such thing as an equation of state, measuring the mass to radius ratio of a star, may be an indicator of this phenomenon.

Because the CFT phase can be better approximated, an equation of state based on phenomenological approach can be a good description. The equation is[11],

$$-P = -\frac{3}{4\pi^2}(1-c)\mu^4 + \frac{3}{4\pi^2}\mu^2 + B_{eff}$$

which a power series expansion about the chemical potential μ. The coefficients come from the microscopic model. The masses for the stars remain of the same order in this model. Still because the models are not well understood measurement of the radius and mass alone will not probe the existence of the quark cores[1].

A useful method that will help probe the existence of this exotic state of matter is the detection of gravity waves[1]. Coalescing binary neutron stars should be an important source of Gravitational Waves and these should be detectable by laser interferometers such as LIGO and VIRGO[12] . Detection of the inspiral of the system using this method, the frequency evolution of the system should would imply the system's "chirp mass",

$$M_{ch} \equiv \mu^{3/5}\mathcal{M}^{2/5}$$

where μ and $\mathcal{M}$ are the reduced and total mass of the binary system respectively. Similarly other information about the system is encrypted in the Gravitational Waves which turns out to be enough to be able to calculate the individual masses of the neutron stars[12].

Furthermore knowledge of the mass of the star would help the understanding of the equation of state which in turn helps to determine the internal structure of the star, say show if the star has a quark core instead of nuclear matter and how dense the core may be. A step in the measured density of the star may show this. These predictions are based on numerical calculations in General Relativity which are nonlinear in nature[12].

Calculations of the thermal conductivity of neutron stars imply a very high thermal conduction. Furthermore, the thermal conductivity of a CFL star is higher than a newborn, which is a direct consequence of the existence of massless Nambu-Goldstone bosons which are the Goldstone modes that are consequence of the Baryon number symmetry breaking $U_B(1)$[13]. This difference in thermal conductivities, would be evident in the radiation spectrum of the star and so it should tell us about structure of the star.

It has also been proposed that the existence of a superconducting rigid crystalline neutron star core may be the source for observable phenomena[1]. Say an some kind of interaction keeps the shape of the core in such a way so that its quadrupole moment is nonzero, Gravitational Waves will be emitted. This has deep implications, since they might be a major contribution to the GR spectrum, If LIGO is unable to measure them, this would impose restrictions on them. LIGO may already be imposing constrains on the parameters used in the QCD calculations. [15]

3.2 Supernovae and neutron stars

Within one minute of the birth of a supernovae, a neutron star cools below about 1 Mev and becomes transparent to neutrinos[1]. While it cools down, it emits neutrinos only until about a million years after its formation, when it starts emitting photons. This implies that information about the interior of the star can be inferred from its temperature (current photon emission) and the time since its formation.

Measurement of incoming neutrinos from newborn neutron stars may provide information about their structure[1][14]. This is based on calculations that indicate that neutrino emission will change due to a second order phase transition inside the star. To be more precise, the cooling of the neutron star accelerates below the critical temperature T_c.

The calculations were presented in [14]. Therefore measurement of incoming neutrinos from recent supernovae events might probe the existence of these phases inside the neutron stars. Furthermore the neutrinos might also help understand the phase transitions as they are undergone by the stars. A clear indication of the current phase of the neutron star, whether hadronic, non-CFL or CFL might be probed then.

4 Conclusions

The phenomenon of Color Flavor Locking (CFL) is a beautiful example of how a confirmed microscopic theory such as Quantum Chromodynamics (QCD) can predict phenomena of astrophysical impact and magnitude. CFL exhibits behavior that was priorly discovered in what seemed unrelated areas of physics such as superconductivity, superfluidity and other Spontaneous Symmetry Breaking (such as Chiral) phenomena. Further experimental techniques will hopefully confirm this prediction or expand it, or if not open roads for more science to be done. Furthermore, Gravitational Wave hunt for signature of these objects may lead to a reshaping of the theory and might even lead to better understanding of gravitational wave detection science.

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