Gapless Color Superconductivity in Quark Matter

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References

  *hep-ph/0302142*

- M. Huang and I. Shovkovy, in preparation...
Phase diagram of QCD

Dense quark matter is a color superconductor!
[Barrios,78], [Bailin & Love,84], [Alford et al.,98], [Rapp et al.,98],…

Where to find CSC?

- Interior of compact stars:
  M-R relation, surface temperature, neutrino flux, magnetic field, glitches, strangelets in cosmic rays, R-mode instability, etc.

- Heavy ion collisions (?)
- Cosmic strangelets (?)
Motivation: compact stars

Color superconductivity $\rightarrow$ gap in quasiparticle spectrum

- Thermodynamic properties (equation of state)
  - mass-radius relation
  - internal star structure
- Transport properties (conductivities, viscosities, mean free paths)
  - cooling rate
  - r-mode instability
  - glitches (crystalline phase)
- Other properties
  - magnetic field generation/penetration
  - rotational vortices
Neutrality vs. color superconductivity

- The “best” 2SC phase appears when $n_d \approx n_u$,
- but neutral matter appears when $n_d \approx 2n_u$
- Electrons do not help (!):

\[ n_d \approx 2n_u \Rightarrow \mu_d \approx 2^{1/3}\mu_u \Rightarrow \mu_e = \mu_d - \mu_u \approx \frac{1}{4}\mu_u \]

Thus, \[ n_e \approx \frac{1}{4^3} \frac{n_u}{3} \ll n_u \]

- Cooper pairing with a mismatch between Fermi surfaces of pairing quarks:

\[ \mu_d - \mu_u = \mu_e \]

Gaps: $(\Delta + \mu_e/2)$ and $(\Delta - \mu_e/2)$
Gapless superconductivity

- Diquark coupling strength $\eta$
  
  (i) “strong”:
  $\eta > \eta_2^{cr} \rightarrow 2SC$

  (ii) “weak”:
  $\eta < \eta_1^{cr} \rightarrow \text{normal}$

  (iii) “intermediate”:
  $\eta_1^{cr} < \eta < \eta_2^{cr} \rightarrow g2SC$

- What is g2SC?
- Is g2SC truly stable?

What are the physical properties of the g2SC at $T = 0$ and $T \neq 0$?
Stability

Eff. potential at $T = 0$  

Eff. potential at $T \neq 0$

Thus, g2SC is stable provided $n_Q = 0$ is enforced \textit{locally}
Quasiparticle spectrum in 2SC phase
Quasiparticle spectrum in g2SC phase

\[ E_{\Delta^-}(p) \]
\[ E_{\Delta^+}(p) \]

\[ \delta \mu - \Delta \]
\[ \delta \mu + \Delta \]

\[ \mu_{ur} \]
\[ \mu^- \]
\[ \mu \]
\[ \mu^+ \]
\[ \mu_{ dg} \]
Temperature dependence of the gap. I.

- Nonmonotonic temperature dependence
- Transitional behavior: g2SC $\rightarrow$ 2SC $\rightarrow$ g2SC $\rightarrow$ normal phase
Temperature dependence of the gap. II.

- Extreme nonmonotonic temperature dependence
- Transitional behavior: normal phase $\rightarrow$ g2SC $\rightarrow$ normal phase
Nonuniversal ratio $T_c/\Delta_0$

- The ratio is *not universal* (unlike in BCS)
- The value of $T_c/\Delta_0$ can be *arbitrarily* large
Summary

- Charge neutrality and $\beta$-equilibrium play very important role in studies of quark matter phases
- Gapless 2SC is a stable ground state of quark matter in a range of coupling strengths
- Gapless 2SC presents an unusual realization of the Higgs mechanism
- Temperature dependence of the gap is nonmonotonic
- Ratio $T_c/\Delta_0$ is nonuniversal, and can be arbitrarily large
- There is more to this …
- Gapless quark matter may turn out to be not just a curiosity…