The surface of a color superconducting strange star

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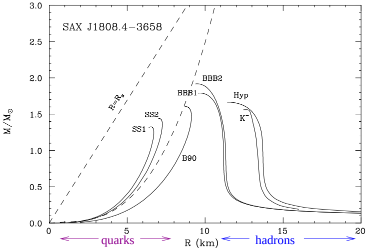
Strange quark matter and strange stars

- Quark stars: are there stars composed uniquely of quark matter?

- Hypothesis(Bodmer '71, Witten '84): strange quark matter (quarks u, d, s) absolutely stable (favored by Pauli principle)
- In Bag models: seems possible (Farhi & Jaffe '84)
- In contrast to neutron stars: self-bound objects (bound by strong interactions)
- Observable through e^+e^- pair production? (Usov '98)



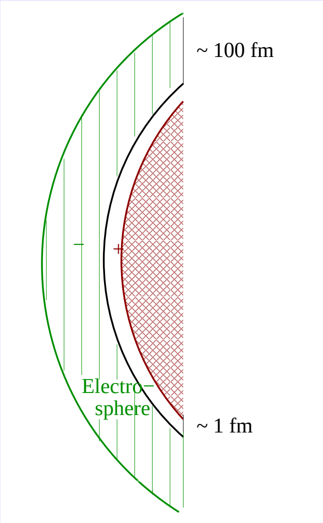
(I. Bombaci '00)

Standard picture of the surface

- Condition: charge neutrality

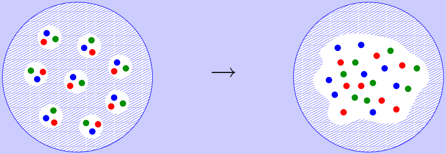
$$\boxed{\frac{2}{3}N_u - \frac{1}{3}N_d - \frac{1}{3}N_s - N_e = 0}$$

- But: $m_s (\approx 150\mathrm{MeV}) > m_u, m_d (\approx 0)$
  $\longrightarrow N_s < N_u, N_d$: quark matter positively charged
- At the interior of the star: compensated by $\rho_e \neq 0$
- At the surface:
  $\rho_q \sim 10^{15}\mathrm{g/cm}^3 \rightarrow 0$ within ~ 1 fm
- Kinetic energy of the electrons
  $\longrightarrow$ electron atmosphere ($\sim$ 100fm)
  (Alcock et al. '86, Kettner et al. '95)
- Very large electric field ($\sim 10^{17}$V/cm)
  $\longrightarrow$ pair creation



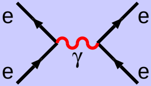
High density and low temperature: why color superconductivity?

- Matter at high density:
  deconfined quark matter

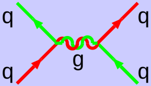


- Naively: Fermi sea of free quarks + attractive interaction → Cooper instability

- Electrons in metals:
  photon exchange repulsive
  phonons ⟶ formation of electron pairs



- QCD (quantum chromodynamics) :
  gluon exchange attractive
  ⟶ formation of quark pairs



Three flavor pairing: "CFL" phase

- Analogy: electron Cooper pairs $\langle e^T \sigma^2 e \rangle \leftrightarrow \langle e_\downarrow^T e_\uparrow \rangle$

- "Diquark condensate" : $\langle \psi^T \mathcal{O} \psi \rangle$

  $\mathcal{O}$: operator in Dirac, colour and flavour space

- Constraint: Pauli principle $\rightarrow \mathcal{O}$ totally antisymmetric

$$\psi = \begin{pmatrix} u \\ u \\ u \\ d \\ \vdots \end{pmatrix}$$

- CFL phase: scalar colour antitriplet diquark

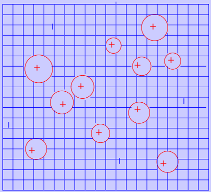
$$\langle \bar{\psi}_{\alpha a A} \epsilon^{iab} \epsilon^{iAB} (\gamma_5 C)_{\alpha\beta} \bar{\psi}_{\beta b B} \rangle \sim \Delta_{ii}$$

- All quarks paired in BCS-type phase

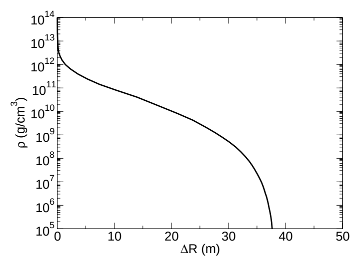
  $\longrightarrow \rho_u = \rho_d = \rho_s$: neutral without electrons

- Surface effects?

Mixed phase at the surface?



- Idea: satisfy charge neutrality globally
  $\longrightarrow$ mixed phase at the surface:
  small "strangelets" (positively charged)
  emerged in electron gas
- Without surface/Coulomb effects: favored (Jaikumar et al. '06)
- Surface region $\sim$ 50 m, no electrosphere, no pair production
- Stability of strangelets (surface effects)?



(Jaikumar et al. '06)

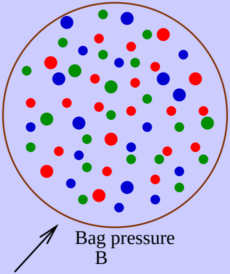
Bag model

- Idea of bag models: simulate confinement via a "bag"
- Quarks "confined" inside the bag by external pressure "B"

- Description of quarks inside the bag:
  solution of the Dirac equation with boundary conditions
- Most simple boundary conditions (MIT Bag model):

$$-i\vec{e}_r\vec{\gamma}\psi = \psi|_{r=R}$$

  (no particle current through the surface)
  $\longrightarrow$ wave function of relativistic particles $\neq 0$ at $r = R$
  $\longrightarrow$ wave function of massive particles suppressed at $r = R$



- Here: bag model + pairing interaction

Formalism: Hartree-Fock-Bogoliubov (HFB) equations

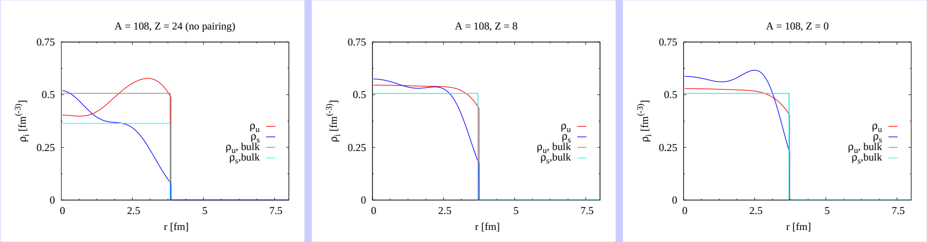
- Treatment of a non-homogeneous system with pairing: HFB equations
- Principle: linearise the interaction assuming $\langle\psi^T \mathcal{O}\psi\rangle \sim \Delta \neq 0$
  look for selfconsistent solution
- Diagonalisation of

$$\begin{pmatrix} h & \Delta^\dagger \\ \Delta & -h \end{pmatrix} \begin{pmatrix} U(\vec{r}) \\ \gamma^0 V(\vec{r}) \end{pmatrix} = \epsilon \begin{pmatrix} U(\vec{r}) \\ \gamma^0 V(\vec{r}) \end{pmatrix}$$

- U and V related by time reversal
- Quantum numbers: coulour, flavour, Dirac (spin)
- h : hamiltonian, $\Delta = \sum_{A=2,5,7} \Delta_A \tau_A \lambda_A$: gap (matrix in coulour and flavour space)

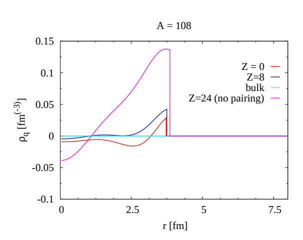
Results: density profiles for a small strangelet

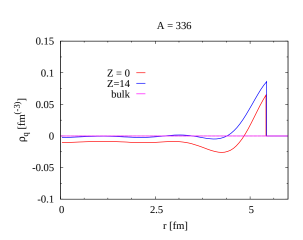
- $A = 108$: Three solutions
  - Without pairing (Z = 24), $E/A = 1047.1$ MeV
  - With pairing, unpaired *u* and *d* quarks at the surface (Z = 8), $E/A = 1024.1$ MeV
  - All quarks paired (Z = 0), $E/A = 1024.3$ MeV

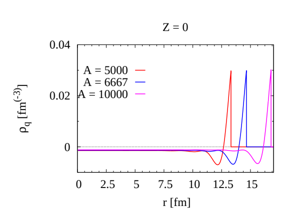


- Effect of pairing: densities of light and strange quarks are much less different

Results: Charge densities for different A



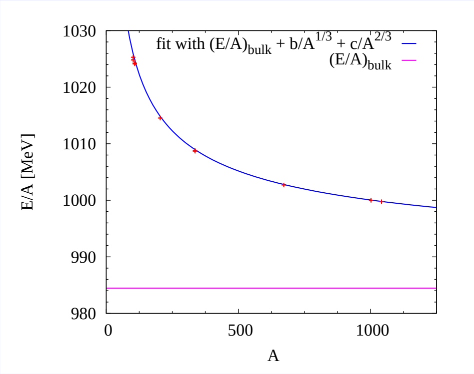




- Charge density much smaller with pairing
- Positively charged layer at the surface ($\sim$ 1 fm) with approximately constant surface charge density
- $Z = 0$ solution: negatively charged layer ($\sim$ 1 fm) reduces surface charge
- Estimate surface electric field (remind $E_{cr} \sim 1 \times 10^{16}$ V/cm)
  - Unpaired $E_{sur} \sim 10^{19}$V/cm
    (remark: larger than standard value because of surface charge, (Usov '04))
  - With pairing $E_{sur} \sim 7 \times 10^{18}$V/cm: slightly smaller than unpaired
    No significant difference between the two different pairing scenarios

Results: energy per baryon

- Energy per baryon as function of A: well reproduced by liquid drop type formula with surface and curvature term



Summary and Outlook

Summary:

- Study pairing effects on the density distribution in lumps of strange quark matter
- Different scenarios
  - Solution with $Z = 0$: no electrons for small strangelets (no droplets), postively charged surface layer remains for large systems
  - Solution with $Z \neq 0$ (some unpaired quarks): $Z \ll Z_{\text{no pairing}}$ postively charged surface layer
- Surface electric field slightly reduced due to pairing (needs some work...)

Outlook:

- Stability of smaller strangelets
- Correct treatment of electrons/positrons
- Thermal effects ($\longrightarrow$ pair production rate)