Collective excitations in the neutron star inner crust

Micaela Oertel

micaela.oertel@obspm.fr

Laboratoire Univers et Théories (LUTH)
CNRS / Observatoire de Paris/ Université Paris Diderot

Collaborators: L. Di Gallo (LUTH), M. Urban (IPN Orsay)

Physics of Neutron Stars, St. Petersburg, July, 13, 2011

l'Observatoire de Paris — LUTH
Laboratoire Univers et Théories

INTRODUCTION : NEUTRON STAR COOLING AND SUPERFLUIDITY

- Glitches the first evidence for superfluid/superconducting phases inside neutron stars
- Recently : surface thermal emission of Cas A $\rightarrow$ superfluidity in the core
- Surface thermal emission is one of the neutron star observables
- Depends on heat transport properties $\rightarrow$ very sensitive to superfluid and superconducting matter inside the star

COOLING DATA OF CAS A : INDICATION FOR SUPERFLUIDITY IN THE CORE
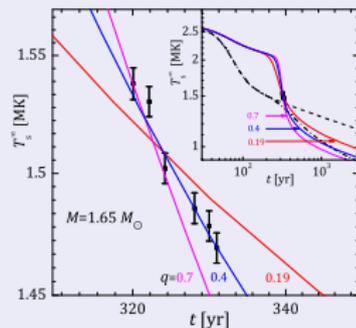
(Shternin et al. MNRAS '11)
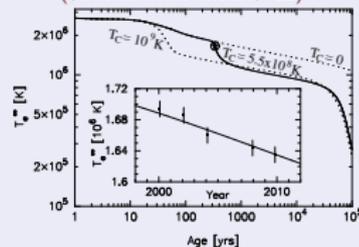
(Page et al. PRL '11)

Neutron star cooling and the inner crust

- The inner crust is composed of nuclear clusters, unbound neutrons and ultrarelativistic electrons
- Close to the core probably the nuclear clusters are deformed → nuclear pasta
- During 50-100 years (crust thermalisation epoch) : cooling behavior mainly influenced by the properties of the inner crust

- Microscopic input to cooling simulations : specific heat, thermal conductivity, neutrino emissivity
- Superfluid neutrons/protons → strong suppression of the contribution to the specific heat (a pair has first to be broken !)
- But with superfluidity collective modes (Bogoliubov-Anderson mode) exist

DIFFERENT CONTRIBUTIONS TO THE SPECIFIC HEAT IN THE INNER CRUST (FORTIN ET AL., PRC '10)
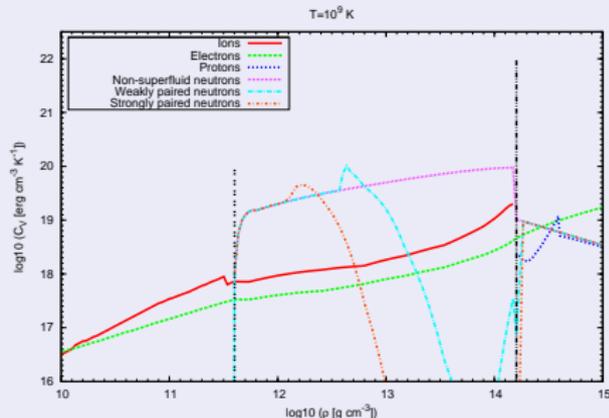
SUPERFLUID HYDRODYNAMICS APPROACH

Advantage of the approach :

- Wavelengths not limited to the size of the Wigner-Seitz cell $\rightarrow$ low-energy part of the spectrum can be correctly described $\rightarrow$ this can give important contributions to thermal properties (Aguilera et al, PRL '09, Pethick et al, PTPS '10, Cirigliano et al, 1102.5379)
- Allows to study the effect of the structure on the excitations.

Our assumptions :

- $T \ll 1$MeV$\sim$ gap energy $\rightarrow$ two superfluids (neutrons,protons) at zero temperature
- Velocities $\ll c$ and densities low enough $\rightarrow$ non-relativistic approximation
- Focus on dynamics of neutron superfluid $\rightarrow$ no Coulomb interaction.

The hydrodynamic equations can be derived from local conservation laws :

- Particle number conservation for neutrons, protons (n, p)
- Energy and momentum conservation (Euler equations) .

Linearizing around stationary equilibrium $\rightarrow$ two sound modes

Collective modes in a periodic slab structure

Inhomogeneous phases $\longrightarrow$ boundary conditions at the interfaces :

- Pressure is continuous
- Contact is maintained $\longrightarrow$ normal components of the velocities are continous
- One surface $\longrightarrow$ normal components of the velocities for p and n are equal

Take the simplest geometry :
structure of periodically alternating slabs
with different proton and neutron densities
(lasagna phase).
Equilibrium properties : RMF model

(Avancini et al, PRC '09)
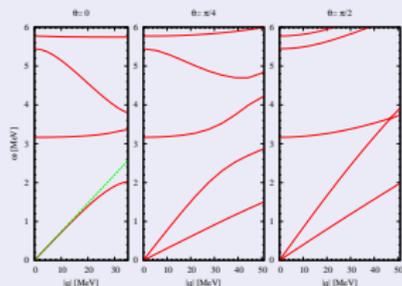

DIAGRAM REPRESENTING THE 1D STRUCTURE
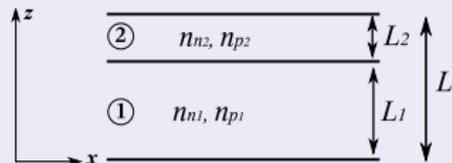
In addition, translational invariance gives the Floquet-Bloch condition :

$$\delta\vec{v}_A(\vec{r} + \vec{R}, t) = e^{i\vec{q}\cdot\vec{R}} \,\delta\vec{v}_A(\vec{r}, t)\,,$$
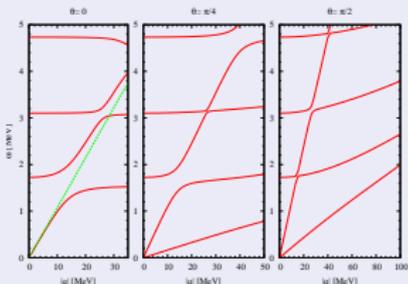
where $\vec{q}$ is the Bloch momentum and $R_z = nL$.

EXCITATION SPECTRUM

DISPERSION RELATIONS FOR WAVES PROPAGATING IN DIFFERENT DIRECTIONS, $n_B = 0.08$ fm^{-3}, RMF MODEL


THE SAME WITH SLY4 INTERACTION

- At $\theta = 0$, one acoustic mode + several optical ones. The slope of the acoustic one (long wavelength limit) corresponds to an average sound velocity.

- At $\theta \neq 0$ a second acoustic mode appears. At small angles this mode corresponds to an excitation of the liquid with protons and neutrons moving out of phase.

- The details of the spectrum depend on the nuclear interaction via the sound velocities.

APPLICATION TO SPECIFIC HEAT
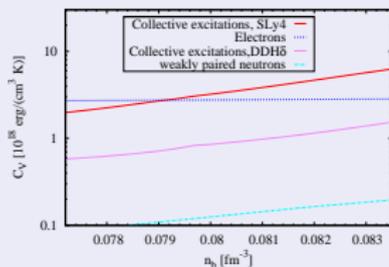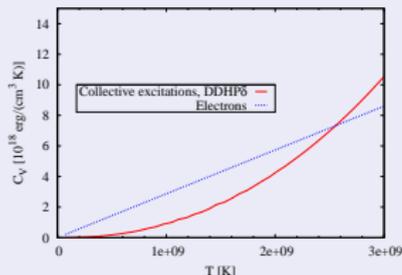
- Superfluidity strongly suppresses the contribution of individual fermions (p, n) to C_V
- But : collective excitations (Bogoliubov-Anderson modes) are induced (the acoustic modes) $\rightarrow$ contribution of collective excitations much more important than individual fermions and comparable to that of e^-.
- At low temperatures, the linear part of the acoustic modes dominate, whereas at higher temperatures the level splitting due to the inhomogeneous structure comes into play.

Summary and outlook

Summary

In order to determine the thermal properties of the neutron star inner crust, the entire excitation spectrum has to be known. We have considered collective excitations taking into account the effects of superfluidity.

- The model is situated in between the long wavelength limit ($|\vec{q}| \ll \pi/L$) and the microscopic approaches applying the Wigner-Seitz approximation ($|\vec{q}| > L$).
- For typical temperatures during the crust thermalization epoch, in particular the lowest lying acoustic mode(s) are important for the thermal properties.

Outlook

The model has to be seen as an exploratory study. The next steps are :

- Coulomb interaction has to be included.
- More complicated geometries (2D-tubes/rods, 3D-droplets/bubbles) should be considered in order to be able to describe the entire inner crust.
- To study the influence on neutrino-matter interactions could be interesting.