Gap Bridging enhancement of modified Urca process in nuclear matter

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Nuclear Physics, Compact Stars, and Compact Star Mergers 2016 (NPCSM2016)
YITP, Kyoto University.

October 27, 2016

Overview

- In superfluid nuclear matter, transport properties (such as neutrino emissivity) are strongly suppressed as $\exp(-\Delta/T)$ by the gap Δ in neutron or proton spectrum.
- Density oscillation of high enough amplitude can unsuppress the exponential suppression of certain transport propetries such as neutrino emissivity and bulk viscosity that are dominated by flavor changing weak processes. The mechanism is called “Gap Bridging”.

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- Some oscillation in neutron star can reach high amplitude.
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  2. **Tidal forces in binary mergers** *D. Tsang et. al PRL 108 (2012)*
  3. **Unstable oscillations of rotating compact stars such as r-modes** *N. Andersson, APJ 502 (1998) 708*

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- Consequences:
    1. enhanced cooling via neutrino emission.
    2. non-linear damping of r-mode itself.

Compression drives the system out of beta equilibrium

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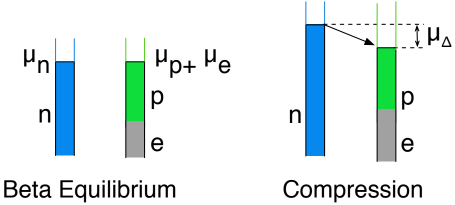
Compression drives the system out of beta equilibrium

- Density compression leads to the change in Fermi momenta.
- Under relatively fast compression the proton Fermi energy is μ_Δ below the neutron Fermi energy.

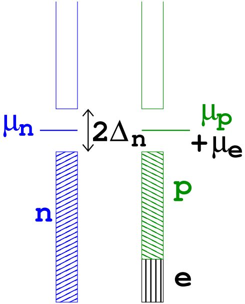
$$\mu_\Delta = \mu_n - \mu_p - \mu_e$$



- An increase in μ_Δ increaes the reaction rate and neutrino emissivity.

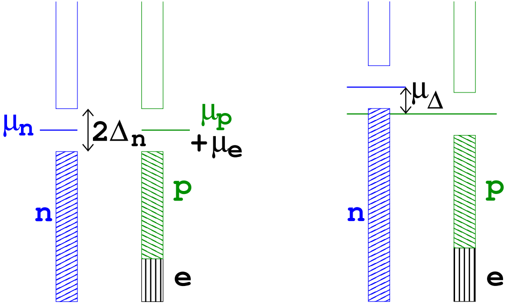
A. Reisenegger, APJ 442:749-757 (1995)

How does “Gap Bridging” work?



No Compression

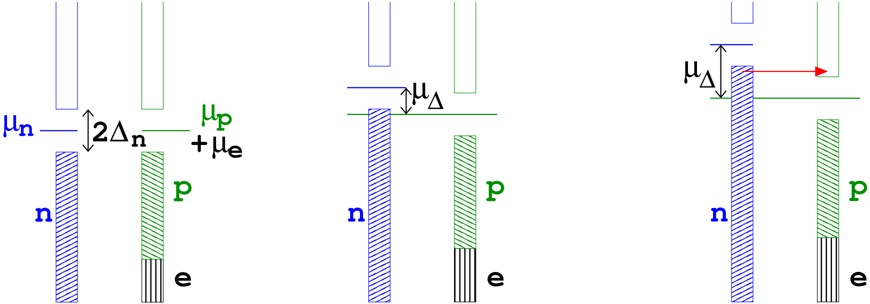
How does “Gap Bridging” work?



No Compression

Slight Compression

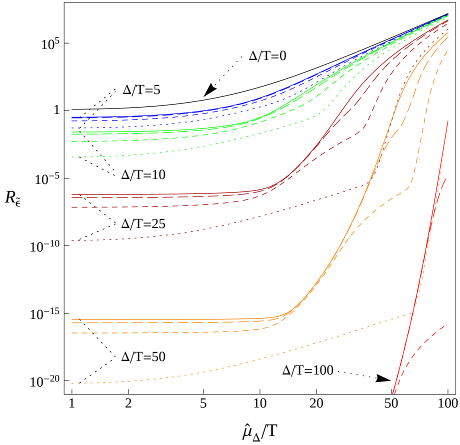
How does "Gap Bridging" work?



No Compression Slight Compression Strong Compression

- At strong compression n $\rightarrow$ p can go but n $\rightarrow$ n and p$\rightarrow$ p are still pauli blocked.
- Gap Bridging is relevant to any reaction where nucleon or quark change flavor.

Previous work: $^1S_0$ neutron pairing and direct Urca



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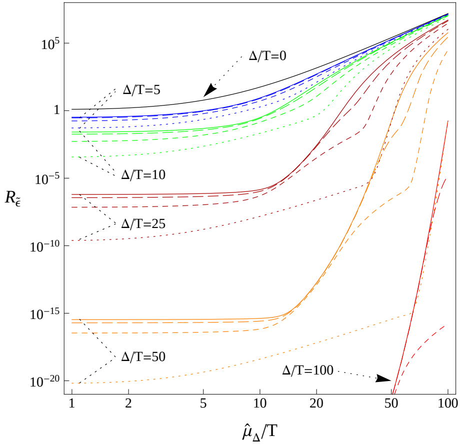

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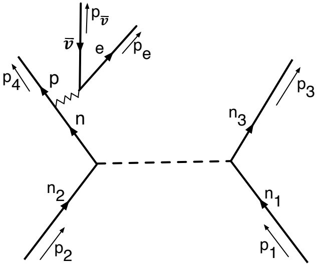
- **Direct Urca** process (n$\leftrightarrow$ p+e+$\bar{\nu}$) is **forbidden** in most of the neutron stars by energy momentum conservation.($p_{Fn} > p_{Fp} + p_{Fe}$)
- In the inner regions of NS, **neutrons pair in $^3P_2$ channel not $^1S_0$.**

Plan

- Previous Work:
  1. Direct Urca process with $^1S_0$ neutron pairing.
- Current Work:
  1. Modified Urca process with $^1S_0$ neutron pairing
  2. Modified Urca process with $^3P_2$ neutron pairing

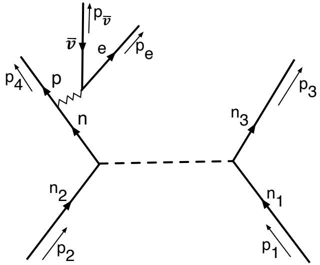
Modified Urca process



$$n + n \to n + p + e^- + \bar{\nu}_e$$
$$p + n + e^- \to n + n + \nu_e$$

- n_1 is “spectator” neutron.
- n_2 is “protagonist” neutron.
- The‘spectator’ neutron, interacting via pion exchange, absorbs the extra momentum.

Modified Urca process



$$n + n \rightarrow n + p + e^- + \bar{\nu}_e$$
$$p + n + e^- \rightarrow n + n + \nu_e$$

- n_1 is “spectator” neutron.
- n_2 is “protagonist” neutron.
- The‘spectator’ neutron, interacting via pion exchange, absorbs the extra momentum.
- No flavor change for spectator particle.
- What role does spectator neutron play?

Gap Bridging enhancement of neutrino emission.

Emissivity (ϵ):

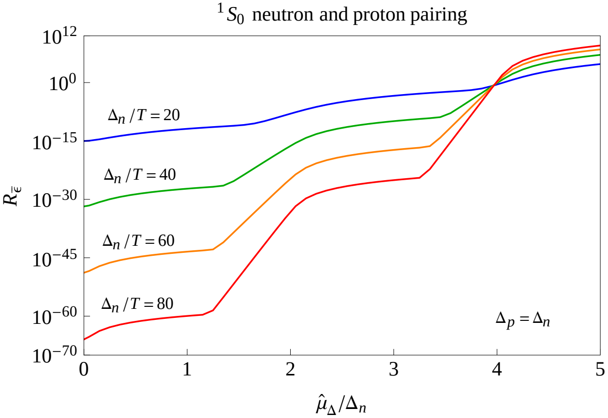
$$\epsilon = \int \left[\prod_{j=1}^{4} \frac{d^3P_j}{(2\pi)^3}\right] \frac{d^3P_e}{(2\pi)^3} \frac{d^3P_\nu}{(2\pi)^3} (2\pi)^4 \delta(E_f - E_i) \times$$
$$\delta^3(\vec{P_f} - \vec{P_i}) E_\nu f_1 f_2 (1 - f_3)(1 - f_4)(1 - f_e) |M_{fi}|^2$$

$$R_\epsilon = \frac{\epsilon(\mu_\Delta/T, \Delta/T)}{\epsilon(0,0)}$$

- R_ϵ is the modification function.

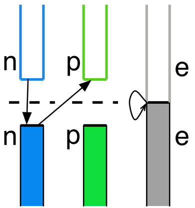
R_ϵ measures how much the emissivity is affected by nonlinear high amplitude effects and by Cooper pairing. Battle between $\exp(-\Delta/T)$ suppression and μ_Δ enhancement.

Emissivity with $^1S_0$ pairing for neutrons and protons



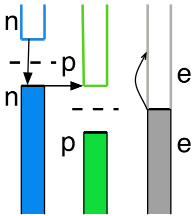
- When $\mu_\Delta = 0$, $R_{\bar{\epsilon}}$ is roughly $\exp[-2\Delta/T]$
- When $\mu_\Delta = 4\Delta_n$, $R_{\bar{\epsilon}}$ is of order 1. **Cancels** $\exp[-\Delta/T]$

Dominant processes at low and high μ_Δ



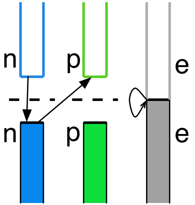
$\mu_\Delta = 0(\exp(-2\Delta/T))$

$\Rightarrow$



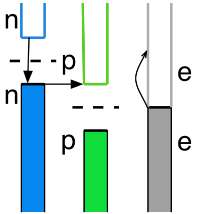
$\mu_\Delta > 0(\exp(-2\Delta/T))$

Dominant processes at low and high μ_Δ

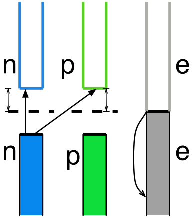


$$\mu_\Delta = 0(\exp(-2\Delta/T))$$

$\Rightarrow$

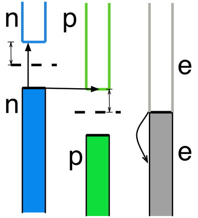


$$\mu_\Delta > 0(\exp(-2\Delta/T))$$



$$\mu_\Delta = 0(\exp(-4\Delta/T))$$

$\Rightarrow$



$$\mu_\Delta > 0(\exp(-2\Delta/T))$$

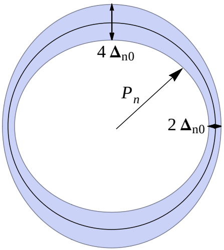
$^3P_2$ neutron pairing

- For the $^3P_2$, there is still a choice of orientation of the condensate: J_z could be 0, $\pm$1, $\pm$ 2.
- Microscopic calculations find that $J_z = 0$ is very slightly energetically favored over the other subchannels.
  T. Takatsuka and R. Tamagaki, PTP (1971),
  L. Amundsen and E. Ostgaard, NPA, (1985)
- However this is not conclusive because of uncertainities in the microscpoic theory.
- We will consider neutron condensates with $J_z = 0$ and $|J_z| = 2$ as we expect these to show different dependencies of the emissivity on temperatue and oscillation amplitude.
  1. For $J_z = 0$ all neutron states at fermi surface are gapped.
  2. for $|J_z| = 2$ there are ungapped nodes at the poles.

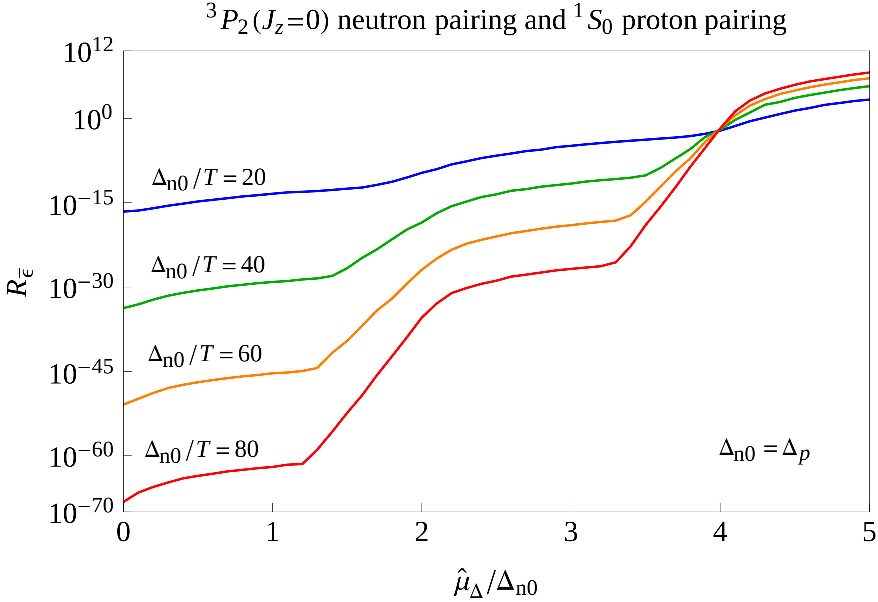
Modified Urca process with $^3P_2(J_z = 0)$ neutron pairing

The angular dependence of the neutron gap in this channel is :

$$\Delta_n(\theta) = \Delta_{n0}\sqrt{1 + 3\,\cos^2(\theta)}$$



- The gap varies between a minimum of Δ_{n0} (around the equator) and $2\Delta_{n0}$ (at the poles) but does not vanish anywhere on the Fermi surface.
- We therefore expect that $^3P_2$ pairing will be qualitatively similar to $^1S_0$ pairing



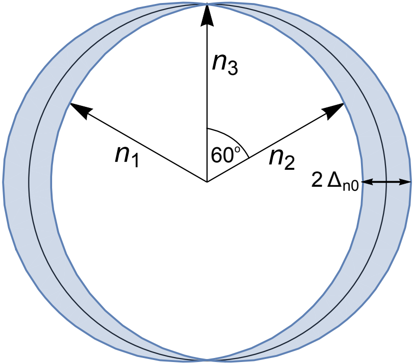
- Emissivity in $^3P_2(J_z = 0)$ is about a factor of 40 less than the $^1S_0$ case.

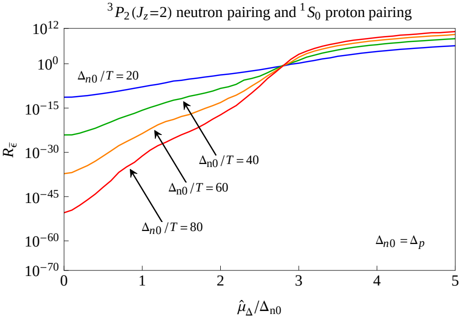
Modified Urca with $^3P_2(J_z = 2)$ neutron pairing

The angular dependence of the neutron gap in $(J_z = 2)$ subchannel is:

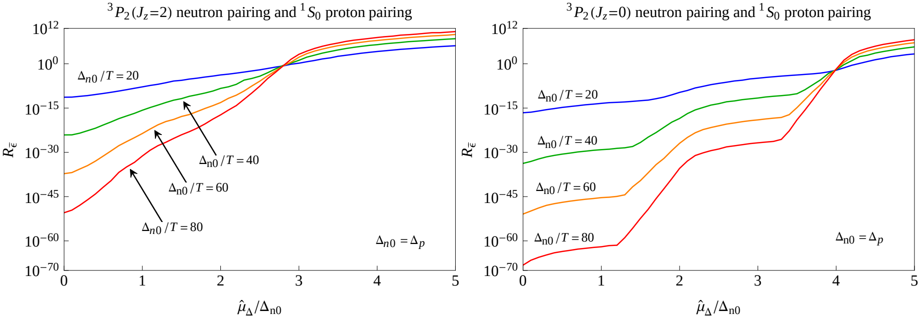
$$\Delta_n(\theta) = \Delta_{n0} \sin(\theta)$$

The Neutron gap vanishes at the poles and has a maximum value of Δ_{n0} around the equator.





$^3P_2(J_z=2)$ neutron pairing and $^1S_0$ proton pairing
10^{12}
10^{0}
10^{-15}
10^{-30}
10^{-45}
10^{-60}
10^{-70}
$R_{\bar{\epsilon}}$
$\Delta_{n0}/T=20$
$\Delta_{n0}/T=40$
$\Delta_{n0}/T=60$
$\Delta_{n0}/T=80$
$\Delta_{n0}=\Delta_p$
0
1
2
3
4
5
$\hat{\mu}_\Delta/\Delta_{n0}$



- Lower suppression of $^3P_2(J_z=2)$ subchannel is expected becuase of the node in the neutron fermi surface.
- For low amplitudes the neutrino emissivity is exponentially suppressed by the gap, roughly as $\exp(-1.73\Delta_{n0}/T)$, as compared with $\exp(-2\Delta_n/T)$ for $^1S_0$ neutron pairing .
- Complete gap bridging happens at $\mu_\Delta = 2.73\Delta_n$ in the case of $^3P_2(J_z=2)$

Conclusions

- We have shown that the exponential suppression of flavor-changing beta processes in superfluid/superconducting nuclear matter can be completely overcome, via the mechanism of gap bridging, by compression oscillations of sufficiently high amplitude, regardless of how low the temperature may be.

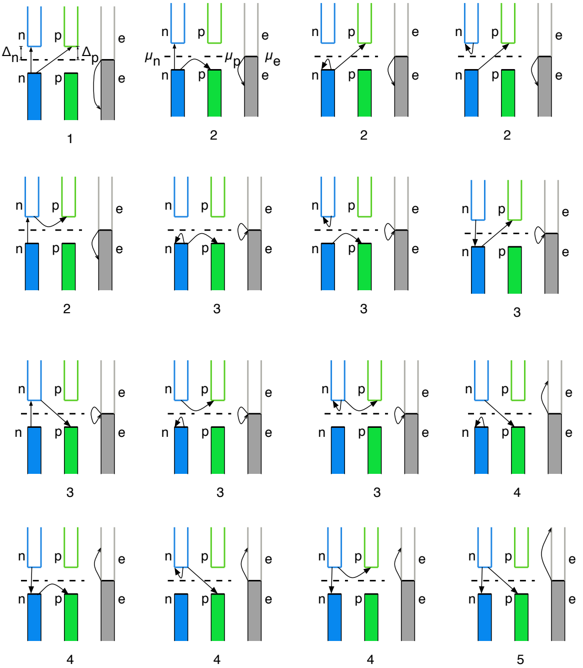
- In $J_z = 0$ subchannel of modified Urca process with $^3P_2$ neutron pairing, the exponential suppression is overcome when $\mu_\Delta \sim 4\Delta_n$

- In $J_z = 2$ subchannel of modified Urca process with $^3P_2$ neutron pairing, the exponential suppression is overcome when $\mu_\Delta \sim 2.73\Delta_n$

- The enhancement of transport properties, such as neutrino emissivity, will lead to enhanced cooling via neutrino emission.

Thank You!!

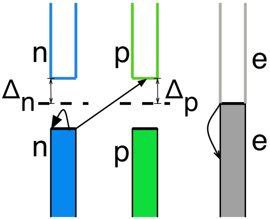
Back Up Slides



- 16 different channels that fall under 5 classes.
- channels under same class have same response to compression oscillation.
- channels under class 3 dominates at low $\delta\mu$ while channel 1 dominates at high $\delta\mu$

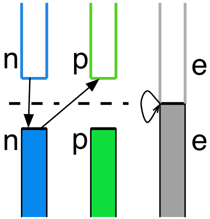
Rules at zero compression ($\delta\mu$=0)

- For each arrow starting at energy $+E$ (i.e. above the Fermi surface): a factor of $\exp(-E/T)$
- For each arrow ending at energy $-E$ (i.e. below the Fermi surface): a factor of $\exp(-E/T)$



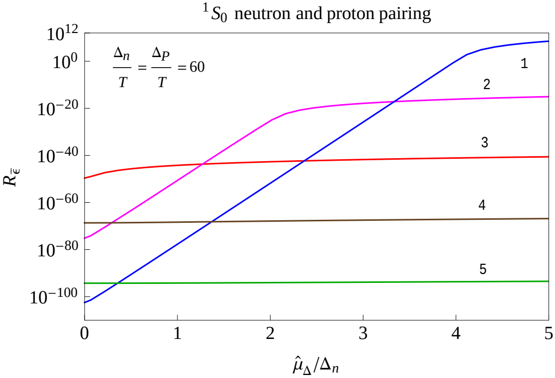
2

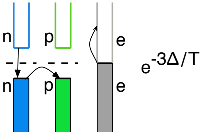
$\exp(-3\Delta_n)$



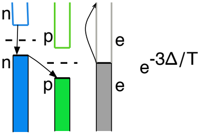
3

$\exp(-2\Delta_n)$

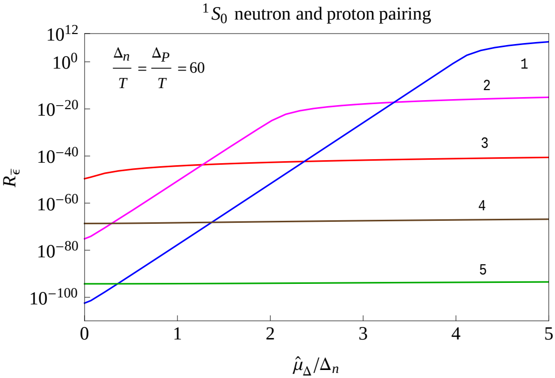

$^1S_0$ neutron and proton pairing
$\frac{\Delta_n}{T} = \frac{\Delta_P}{T} = 60$
$R_{\bar{\epsilon}}$
$\hat{\mu}_\Delta/\Delta_n$
1
2
3
4
5

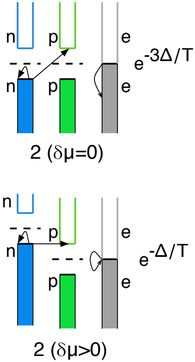

n
p
e
n
p
e
$e^{-3\Delta/T}$

4 (δμ=0)

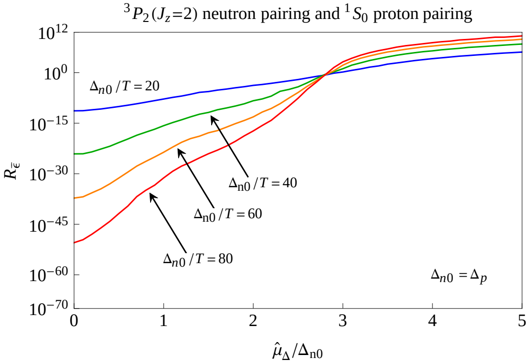

n
p
e
n
p
e
$e^{-3\Delta/T}$

4 (δμ>0)





This explains the step structure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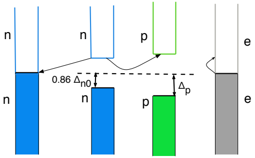
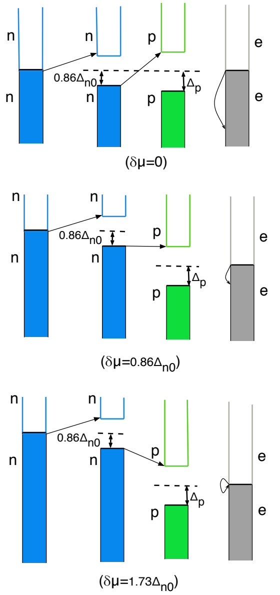
$\Delta_{n0} = \Delta_p$
0
1
2
3
4
5
$\hat{\mu}_\Delta/\Delta_{n0}$


n
n
p
e
0.86 Δ_{n0}
Δ_p
n
n
p
e



- Complete gap bridging happens at $\delta\mu = 2.73\Delta_n$