# Superfluidity in neutron stars

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Superfluidity in neutron stars still remains an open question due to the uncertainties in the interaction and medium corrections. The attractive force required for the formation of Cooper pairs is provided by the interaction between the neutrons. A correct description of the superfluid state is crucial to understanding the cooling of neutron stars. The neutrons pair in the inner layers of the crust and in the outer layers of the core of the star. Using pure neutron matter as an approximation to neutron star matter (which is asymmetric matter with more neutrons than protons), I will discuss the recent approaches to neutron superfluidity both in the crust and core of the star including medium corrections.

## 1. Introduction

Neutron stars, the end product of a type II supernova, are extremely dense and compact stellar objects with a radius of $10-12$ km and density $\sim 10^{14}$ g/cc. Held together by gravity, the stars exhibit very rich structures, with the outer layers of the star's crust containing terrestrial nuclei which progressively become neutron rich radially inwards, while the exact composition of the inner core is yet an open question. For an excellent review on neutron star structure, we refer the reader to [1]

The neutrons present in the inner layers of the outer crust as well as in the outer layers of the core are believed to be in the superfluid state. In fact the idea of neutron superfluidity as a generalisation of superconductivity was formulated as early as 1960 by Migdal, who also subsequently predicted a gap of 1 MeV. In the case of nucleons, the attractive part of the interaction provides the required mechanism for the formation of Cooper pairs. Neutron star matter is highly asymmetric with the neutrons constituting 95% and protons the remaining 5% of the matter in the crust and the core. Therefore, the neutrons in the crust and the core can pair to form a superfluid, while the protons pair in the core.

Superfluidity has been established as an essential ingredient to explain the cooling data of neutron stars. However, the exact dependence of the gap or the transition temperature on density is not completely understood [2, 3]. The difficulty arises due to uncertainties in the two-body interaction that serves as an input to the BCS gap equation and in the medium corrections. In the outer core of the star, pairing occurs in the $^1S_0$ channel in the spin singlet state, where the interaction becomes attractive for the Fermi momentum, $k_F$, in the range $(0.1\,\mathrm{fm}^{-1}, 1.2\,\mathrm{fm}^{-1})$. The pairing gap at the BCS level in this channel is completely determined by the two-body physics. Hence modern $NN$ interactions that reproduce the two-body elastic phase shifts yield identical pairing gap in the $^1S_0$ channel. However, once medium corrections and/or higher-body effects such as the $3N$ force is included, model dependence sets in, even in the $^1S_0$ channel. The situation is very different in the $^3P_2 - ^3F_2$ channel, where the pairing occurs in the spin triplet state, at densities in the outer layers of the core, that is, $k_F \geq 1.4\,\mathrm{fm}^{-1}$. While the exact densities at which the gap closes in the triplet channel is not well established, the pairing gaps themselves are model dependent. This situation arises because at such high densities, the two-body interactions are no longer phase shift equivalent and high densities also warrants the inclusion of medium effects and higher-body forces.

In addition to the uncertainties in the input interactions, beyond BCS corrections are very sensitive to the approximations used at the many-body level. Hence, the pairing problem sees an interplay of few and many-body

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physics and has thus remained an open problem.

Nuclear structure has experienced a renaissance over the last three decades as ideas of effective field theories and renormalization group has allowed the creation of effective interactions in the two-body sector which are model independent as opposed to the more conventional realistic interactions [4]. The model independence becomes important when two-body interactions are used as inputs in many-body calculations. The effective interactions at the two-body level usually depend on a renormalization group scale and dependence of observables on this scale in a many-body calculation signals missing medium and higher-body interactions. Effective field theory then dictates a systematic path to including these effects.

In our approach to the pairing problem in neutron stars, we approximate the asymmetric nuclear matter by pure neutron matter. We then use the effective two-body interactions built via the renormalization group approach, usually referred to as $V_{\text{low k}}$ and $V_{\text{srg}}$ in the literature, as input to the gap equation to study pairing within the BCS approximation as well as beyond and use the dependence of the calculated gap on the renormalization scale as a signature of missing medium and/or many-body corrections. We have studied the gap both in the singlet [5–7] and in the triplet channel [8] in pure neutron matter as well as included corrections from the medium in the form of screening in the singlet channel [7]. Further we also include the correlations that exist before the transition to the superfluid phase between the quasi-neutrons via the Nozière-Schmitt-Rink (NSR) approach. The effect of these correlations is tracked in the transition temperature [6].

In the singlet channel, the medium correction leads to a screened interaction calculated via the particle-hole bubble series. The non-local nature of the effective interactions require us to approximate the particle-hole interaction in the higher-order bubbles. This approximation is done by (1) the Landau approximation and (2) the Skyrme interaction. Both these interactions allows one to calculate the particle-hole bubble diagrams exactly. With the Landau approximation, we note that the interaction is both screened and anti-screened, while the anti-screening disappears once the momentum dependence in the interaction is included via the Skyrme forces.

In the triplet channel, we remove the uncertainties in the phase inequivalence of the input interaction by choosing a particular realistic interaction and its renormalization group evolved effective interactions, so that the phase shift of the realistic interaction (bare) are preserved by construction during the renormalization flow. While the value of the gaps obtained for difference classes of realistic two-body interactions may not agree, within a class of realistic interactions and its corresponding effective interactions, one can study the dependence on the renormalization scale which signals the missing many-body and medium corrections [8].

Most of the work in the singlet channel has been carried out in collaboration with Michael Urban, IPN, Orsay, France, while the studies in the triplet channel has been in collaboration with Sarath Srinivas S. at IIT Madras.

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