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# Superfluid dynamics in neutron stars

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Produced during gravitational-core collapse supernova explosions with initial temperatures as high as ~$10^{12}$ K, neutron stars cool down to temperatures $10^9$ K within a few days. The very dense matter in their interior is expected to undergo various quantum phase transitions analogous to those observed in terrestrial laboratories. Similarly to electrons in conventional terrestrial superconductors, free neutrons in the inner crust and the outer core of neutron stars are predicted to form a Bardeen-Cooper-Schrieffer (BCS) condensate of Cooper pairs. Nuclear superfluidity has found support from the rapid decline of luminosity of the Cassiopeia A remnant and has been corroborated by radio-timing observations of frequency glitches in numerous pulsars.

Despite the importance of the superfluid dynamics for interpreting these latter astrophysical phenomena, most microscopic calculations of the nuclear pairing properties have been carried out so far for static situations. We have recently studied the dynamics of hot neutron-proton superfluid mixtures within the self-consistent time-dependent nuclear energy density functional theory [1,2]. In application to neutron stars, we have computed $^1S_0$ neutron and proton pairing gaps in the homogeneous core in the presence of arbitrary currents and we have determined the mutual neutron-proton entrainment coupling coefficients [3].

We have also shown within the same framework that there exists a dynamical "gapless"state in which nuclear superfluidity is not destroyed even though the energy spectrum of quasiparticle excitations exhibits no gap. The absence of an energy gap leads to a nucleon specific heat that is very different from that in the classical BCS state (in the absence of superflows). The implications for the cooling of neutron stars will be discussed.

[1] N. Chamel & V. Allard, Phys. Rev. C **100**, 065801 (2019).
[2] V. Allard & N. Chamel, Phys. Rev. C **103**, 025804 (2021).
[3] V. Allard & N. Chamel, Universe **7**, 470 (2021).

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