

Fellowship Report

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October 15, 2012

1 Executive Summary

There were a number of accomplishments over the course of my JSA fellowship. These span a number of fields: topological structures in exotic phases in neutron stars, analogous structures in atomic-trap BECs, and an unusual phase of ultra-dense helium that could conceivably exist in white dwarfs.

2 Vortons

Vortons are topological solitons that can exist when two species that repel one another both wish to condense in the same region. If the species that succeeds in forming the bulk develops a vortex loop, the other species may condense in its core. If the inner species carries angular momentum, it will provide protection against the shrinking of the vortex loop.

One example of such a system is the CFL+K⁰ phase of high-density QCD that is a candidate phase for neutron star cores. In this phase the neutral and charged “kaons” (quark-quark pairs that are analogous to the familiar kaons) both wish to condense and exclude the other. For stability, vortons in this case must be electrically charged and to maintain the neutrality of the surrounding system, should attract electrons to cancel any long-range coulomb energies. In Ref. [1] we considered how the charge shielding these electrons provide affect the stable radii of such vortons.

Since the necessary requirements for a system to support vortons are quite generic, we also considered some realistic condensed matter systems that could conceivably be built with current techniques and numerically studied the vortons that those systems could support. Vortons in this case are simpler (since they are stable without being charged). We found that with realistic setups

it should be possible to construct stable vortons with radii on the size of micrometers [2]. These two and previous works also led to a talk at Tel Aviv University[3].

3 Ultra-dense Helium

Helium white dwarfs (HeWDs) are stars which have finished fusing hydrogen into helium but do not have extreme enough conditions to fuse helium into carbon. Eventually such an object collapses in the familiar way into a white dwarf, meaning that its size is sustained by electron degeneracy pressure. If the central density is high enough and the core temperature low enough, it is conceivable that the helium nuclei (*not* atoms) there condense into a superconducting BEC with a background charge-neutralizing degenerate electron gas.

In Ref. [4] we demonstrated that this system contains a very unusual gapless quasiparticle which depends crucially on both the dynamical response of the degenerate electrons and the condensed nature of the helium. The gaplessness of this mode means that at low temperatures, where gapped modes might be Boltzmann-suppressed, this mode will dominate the dynamics and might qualitatively alter the properties this phase exhibits, or cause the condensed phase to dramatically differ from a plasma or crystalline phase. Indeed, we demonstrated that the heat capacity of the condensed phase is much lower than those other phases.

If the gapless mode really does dominate the dynamics at reasonable astrophysical temperatures, it is important to understand how those quasiparticles might interact and decay. In Ref. [5] we considered how the presence of this mode would contribute to the star's neutrino luminosity. We found that if the critical temperature for the condensed phase were high enough, neutrino emission from the core would be competitive with the photon emission from the surface, and these stars might cool faster than conventional models might predict. This is an interesting observable consequence—and could possibly explain the dearth of dim helium white dwarfs: astronomers expect to be able to see cool HeWDs but have not yet found any, while they have found a number of hotter stars of that type.

This drove us to study the thermodynamics of the condensed phase, and to try to determine the critical temperature of the condensate. There were estimates that the critical temperature would be relatively large compared to the free gas critical temperature. The question was: how much higher? The phase diagram of this system was significantly more subtle than expected. In fact,

as discussed in Ref. [6] we now expect that the condensed phase undergoes two phase transitions: a first order transition at low temperature and a second order transition at the free gas critical temperature, dashing our hopes for a very high critical temperature that might make the phase astrophysically relevant. However, if the uncondensed phase is qualitatively different from a free gas, this conclusion may be in error and it may still be possible that a helium condensate play an important role in the dynamics of cool HeWDs.

4 Current and Future Work

The JSA fellowship has certainly allowed me to grow as a researcher, and has provided me with excellent opportunity as a graduate student. Using the travel funds I plan on traveling this fall to the west coast to visit some collaborators and colleagues, and has also, as discussed, enabled me to pursue multiple lines of research this year. During the time of this fellowship I have also considered the application of Langevin techniques to problems in nuclear physics; unfortunately, some of the tricks that one can use for very simple examples seem to fail for more realistic models, so we set this line of research aside. However, I have recently returned to thinking about lattice techniques, this time focusing on the possibility of extracting S-matrices for some simple multi-channel problems in an analogous way that one can use Lüscher's formula to determine the phase shift from two-body finite-volume energy eigenstates. This work, while not yet complete, was begun in the midst of the duration of the JSA fellowship. In the future, I may return to the question of the thermodynamics of condensed ultra-dense helium, as there may be qualitative changes due to the electromagnetic interactions in the uncondensed phase.

References

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- [3] Vortons: Stable vortex loops, 2012. High energy seminar, February 7, Tel Aviv University, Tel Aviv, Israel.
- [4] Paulo F. Bedaque, Evan Berkowitz, and A Cherman. Nuclear condensate and helium white dwarfs. *The Astrophysical Journal*, 749(1):5, 2012, nucl-th/1111.1343.
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- [6] Paulo F. Bedaque, Evan Berkowitz, and Srimoyee Sen. Thermodynamics of nuclear condensates and phase transitions in white dwarfs. 2012, astro-ph/1206.1059.