Superfluid-superconductor relationship is detailed

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Scientists have studied superconductors and superfluids for decades. Now, researchers at Washington University in St. Louis have drawn the first detailed picture of the way a superfluid influences the behavior of a superconductor. In addition to describing previously unknown superconductor behavior, these calculations could change scientists' understanding of the motion of neutron stars.

A neutron star, the high-density remnant of a former massive star, is thought to contain both a neutron superfluid and a proton superconductor at its core. Despite widespread agreement that neutron stars contain both materials, superfluid-superconductors have not been widely studied.

"Not many people have thought seriously about the interactions between a superfluid and a superconductor that are co-existing like this," said Mark Alford, associate professor of physics and lead author of the paper published in the July issue of *Physical Review B,* "They tended to treat the two components separately."

Super Phenomena

Separately, the two phenomena are well understood. A superconductor allows a flow of current without resistance. Similarly, a superfluid flows without friction. Unlike superconductors and superfluids, a superfluid-superconductor does not exist on earth. But, understanding its hybrid behavior may be a first step toward creating one in the lab and understanding what goes on inside neutron stars.

In addition to conducting current without resistance, superconductors also exclude magnetic fields. Neutron stars have massive magnetic fields, but scientists do not know how a superconductor behaves in the presence of this field, specifically whether it will be a type I or type II superconductor. A type I superconductor forces a magnetic field around its exterior. A type II superconductor, however, strikes a compromise, letting the magnetic field pass through tiny non-superconducting holes called flux tubes. Type II superconductors permit one unit of magnetic field per flux tube.

Whether a superconductor is type I or type II depends on a value called kappa. If kappa is greater than a set critical value, the superconductor is type II. Likewise, if kappa is less than the critical value, the superconductor is type I. Add a superfluid, however, and these calculations show that the superconductor's boundary shifts, changing the critical value of kappa and causing exotic behavior at the boundary.

Living on the Edge

Ariel Zhitnitsky at the University of British Columbia was the first to report this boundary shift. Curiosity piqued by the shift, Alford and his collaborator, graduate student Gerald Good, decided to take a closer look at the boundary.

"We found that the boundary wasn't just shifted, but new behavior appeared when the superconductor is on the edge, between type I and type II," said Alford. Since superconductors and superfluids are older physics, Alford added, "We were surprised that there was anything new to mine here."

To understand the boundary shift, Alford and Good examined two interactions between the superfluid and superconductor. The first had a superconductor either attracting or repelling a superfluid. The second had a flowing superconductor causing a superfluid to flow either with it or against it.

Exotic Behavior at the Shifted Boundary

Alford and Good found that the two superconductor-superfluid interactions (attractive/repulsive and flow) had opposite effects on the boundary shift and produced different, but equally exotic, boundary behavior.

The attractive/repulsive interaction increased kappa, favoring a type I superconductor and creating intermediate type II states near the boundary. These intermediate states resemble type II because they have flux tubes; but strangely, more than one unit of magnetic field appears to exist in each. Depending on the parameters, an infinite number of intermediate type II states exist, with any number of magnetic field units in each flux tube.

Unlike the attractive/repulsive interaction, the flow interaction decreased kappa, favoring a type II superconductor. Instead of intermediate type II states, the flow interaction creates meta-stable regions on either side of the boundary. Specifically, in these regions a superconductor that should be type II can get stuck as type I and vice versa. A familiar example of similar behavior is when, under the right conditions, water remains a liquid despite freezing temperatures.

Passing the Baton

Just as Zhitnitsky's work inspired Alford and Good to look closer at the type I/type II boundary, this work has already spurred others in new directions. A group at Dartmouth College is confirming some behavior seen by Alford and Good, but the Dartmouth results favor a different scenario for the intermediate type II phases (unpublished).

The Dartmouth group is not seeing multiple units of magnetic field in one flux tube, but flux tubes that are a fixed distance apart (with one unit of magnetic field each). These flux tubes tend to "stick together" rather than spread out as far as possible, as in normal type II superconductors. Alford and Good said they could not rule out this possibility due to limitations in the simplified model and in computing capacity.

"The Dartmouth group is seeing similar intermediate phases," said Good, "but slightly different behavior. That's the next step in our research and it's already being done, which is pretty neat."

Source: Washington University in St. Louis

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