Researchers develop superconducting quantum refrigerator

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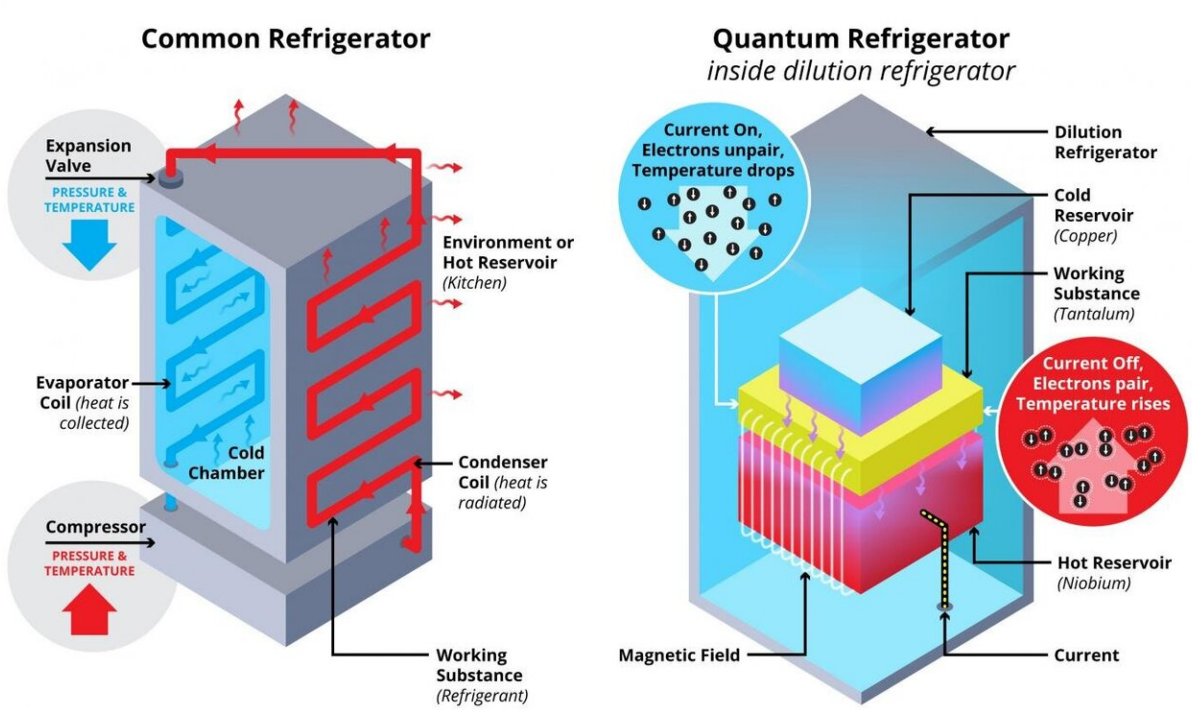

The superconductor fridge is similar to a conventional refrigerator, in that it moves a material between hot and cold reservoirs. However, instead of a refrigerant that changes from a liquid state to a gas, the electrons in a metal change from the paired superconducting state to an unpaired normal state. Credit: University of Rochester illustration / Michael Osadciw

Imagine a refrigerator so cold it could turn atoms into their quantum states, giving them unique properties that defy the rules of classical physics.

In a paper published in *Physical Review Applied*, Andrew Jordan, professor of physics at the University of Rochester, and his graduate student Sreenath Manikandan, along with their colleague Francesco Giazotto from the NEST Istituto Nanoscienze-CNR and Scuola Normale Superiore in Italy, have conceived an idea for such a refrigerator, which would cool atoms to nearly absolute zero temperatures (about minus 459 degrees Fahrenheit). Scientists could use the refrigerator, which is based on the quantum property of superconductivity, to facilitate and enhance the performance of quantum sensors or circuits for ultrafast quantum computers.

What Is Superconductivity?

How well a material conducts electricity is known as conductivity. When a material has high conductivity, it readily allows an electric current to flow through it. Metals, for instance, are good conductors, while wood, or the shielding wrapped around metal wires, are insulators. But, while metal wires are good conductors, they still encounter resistance due to friction.

In an ideal scenario, a material would conduct electricity without encountering resistance; that is, it would carry a current indefinitely without losing any energy. This is precisely what happens with a superconductor.

"When you cool down a system to extreme temperatures, the electrons enter a quantum state where they behave more like a collective fluid that flows without resistance," Manikandan says. "This is achieved by electrons in a superconductor forming pairs, known as cooper pairs, at very low temperatures."

Researchers believe all metals can become superconductors if they are made cold enough, but each metal has a different "critical temperature" at which its resistance disappears.

"When you reach this magical temperature—and it's not a gradual thing, it's an abrupt thing—suddenly the resistance just drops like a rock to zero and there is a phase transition that happens," Jordan says. "A practical superconducting fridge, as far as I know, has not been done at all."

Similarities To A Traditional Refrigerator

The superconducting quantum refrigerator uses the principles of superconductivity to operate and generate an ultra-cold environment. The cold environment then is conducive to generating the quantum effects required to enhance quantum technologies. The superconducting quantum refrigerator would create an environment whereby researchers could change materials into a superconducting state—similar to changing a material to a gas, liquid, or solid.

While superconducting quantum refrigerators would not be for use in a person's kitchen, the operating principles are quite similar to traditional refrigerators, Jordan says. "What your kitchen fridge has in common with our superconducting refrigerators is that it uses a phase transition to get a cooling power."

If you go into your kitchen and stand by your refrigerator you will notice it is cold on the inside, but warm on the backside. A conventional refrigerator does not operate by making its contents cold, but by removing heat. It does this by moving a fluid—the refrigerant—between hot and cold reservoirs, and changing its state from a liquid to a gas.

"Refrigerators don't create cold out of nothing," Jordan says. "There's a principle of conservation of energy. Heat is a kind of energy, so the fridge takes heat from one region of space and takes it to another region."

In a conventional refrigerator, the refrigerant in a liquid state passes through an expansion valve. When the liquid is expanded, its pressure and temperature drop as it transitions into a gaseous state. The now cold refrigerant passes through an evaporator coil on the inside of the fridge box, absorbing heat from the refrigerator's contents. It is then re-compressed by a compressor powered by electricity, raising its temperature and pressure even more and turning it from a gas to a hot liquid. The condensed hot liquid, hotter than the outside environment, flows through condenser coils on the outside of the fridge, radiating heat to the environment. The liquid then reenters the expansion valve and the cycle repeats.

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"We are doing the exact same thing as a traditional fridge, but with a superconductor," Manikandan says.

The Inner Workings Of A Superconducting Quantum Refrigerator

In the superconducting quantum fridge, researchers place a layered stack of metals in an already cold, cryogenic dilution refrigerator:

- The bottom layer of the stack is a sheet of the superconductor niobium, which acts as a hot reservoir, akin to the environment outside a traditional refrigerator
- The middle layer is the superconductor tantalum, which is the working substance, akin to the refrigerant in a traditional refrigerator
- The top layer is copper, which is the cold reservoir, akin to the inside of a traditional fridge

When the researchers slowly apply a current of electricity to the niobium, they generate a magnetic field that penetrates the middle tantalum layer, causing its superconducting electrons to unpair, transition to their normal state, and cool down. The now cold tantalum layer absorbs heat from the now warmer copper layer. The researchers then slowly turn off the magnetic field, causing the electrons in the tantalum to pair and transition back into a superconducting state, and the tantalum becomes hotter than the niobium layer. Excess heat is then transferred to the niobium. The cycle repeats, maintaining a low temperature in the top copper layer.

This is similar to the refrigerant in a traditional refrigerator, transitioning from cycles of cold where it is expanded into a gas and hot where it is compressed into a fluid. But because the working substance in the quantum superconducting refrigerator is a superconductor, "it's instead the cooper pairs that unpair and get colder when you apply a magnetic field slowly at very low temperatures, taking the current state-of-the-art refrigerator as a baseline and cooling it even more," Manikandan says.

While you use your kitchen refrigerator to store milk and vegetables, what might a researcher put in a superconducting quantum fridge?

"You use a kitchen refrigerator to cool down your food," Jordan says. "But this is a super, super cold refrigerator." Instead of storing food, the superconducting quantum refrigerator could be used to store things like qubits, the basic units of quantum computers, by placing them on top of the stack of metals. Researchers could also use the fridge to cool quantum sensors, which measure light very efficiently and are useful in studying stars and other galaxies and could be used to develop more efficient deep tissue imaging in MRI machines.

"It's really kind of amazing to think about how this works. It's all basically taking energy and converting it into a transformative heat."

More information: Sreenath K. Manikandan et al. Superconducting Quantum Refrigerator: Breaking and Rejoining Cooper Pairs with Magnetic Field Cycles, *Physical Review Applied* (2019). DOI: 10.1103/PhysRevApplied.11.054034

Provided by University of Rochester

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