Physicists investigate electron fractionalization into not two, but three components

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One of the many intriguing puzzles in physics is the strange behavior of the electron as it fractionalizes into two separate quasiparticles. These quasiparticles, called spinons and chargons (or holons), carry the electron's spin and charge, respectively. In a new study, physicists Cenke Xu and Subir Sachdev of Harvard University have investigated this phenomenon, called spin-charge separation, and have developed a model that unifies two previous theories to propose a more complete electron fractionalization process.

In order for electrons to fractionalize, many of them must be tightly confined so that they repel each other. In trying to stay apart, the electrons modify how they behave so that their magnetism (which is associated with spin) and charge separate into the two new quasiparticles. In condensed matter physics, quasiparticles are phenomena of groups of particles that behave as if they were particles. Physicists first observed spinons and holons in 2009 by confining electrons in a quantum wire and detecting how electrons in a nearby metal could tunnel into the quantum wire by splitting into the two quasiparticles.

One unsolved part of electron fractionalization involves figuring out what happens to an electron's Fermi statistics after spin-charge separation. Fermi statistics describe the properties of all particles that obey the Pauli Exclusion Principle, which says that no two of these particles can occupy the same quantum state. In the Standard Model, these particles include all the fermions, one of which is the electron. The question that physicists ask is, when the electron fractionalizes into its spin and charge, where do its Fermi statistics go?

As Xu and Sachdev explain in their new study, there are two main answers to this question. Put simply, the Fermi statistics have previously been proposed to be either with the spin or with the charge. But Xu and Sachdev suggest that these seemingly divergent possibilities can be unified into one picture. The physicists suggest that the electron fractionalizes into not just two, but three components that carry the electron's spin, charge, and Fermi statistics. While spinons and chargons (or holons) are the first two carriers, the Fermi statistics are carried by a Majorana fermion. The physicists also illustrated these ideas on a honeycomb lattice to demonstrate how the proposal works.

"A central problem in quantum physics is understanding the varieties of exotic quantum states of many-electron systems: their long-range quantum entanglement and the nature of their quasiparticle excitations," Sachdev told PhysOrg.com. "We show that most previous proposals can be unified under a single theory in which the central quasiparticle is a Majorana particle which carries only the Fermi statistics of the electron, but neither its spin nor its charge. Our theory leads to new types of quantum many-electron states, and also provides an improved and unified understanding of the previous disparate proposals."

Interestingly, the Higgs boson or something similar to it may also play a role in Xu and Sachdev's model. As they explain, the Majorana particle can undergo quantum transitions that are associated with the Higgs.

"Our parent Majorana liquid can exhibit quantum phase transitions to other many-electron states, in which there is qualitative change in the nature of the forces between the quasiparticles," Sachdev said. "These forces are mediated by particles called 'gauge bosons,' which are similar to gauge bosons in elementary particle physics: for example, the photon that mediates the electromagnetic force, the gluon that is associated with the strong force, and the W and Z bosons that are associated with the weak force. Also in elementary particle physics, the Higgs boson is needed to make the weak force short-ranged; without it, the elementary particles would be in a new phase with a long-ranged weak force that has been presumed to exist only moments after the Big Bang. Similarly, among our many possible quantum states with different types of entanglement and quasiparticles, there are quantum transitions associated with changes in the density of bosons very similar to the Higgs boson of elementary particle physics."

Overall, a better understanding of electron fractionalization could have useful applications, such as in designing quantum computers and achieving quantum entanglement at long scales.

"Our theory leads to a deeper understanding of the different types of quantum entanglement in many-electron states at very low temperatures," Sachdev said. "Quantum computers manipulate the entanglement in a complex manner, and we have shown there is a richer variety of available entangled states and have unified their understanding."

More information: Cenke Xu and Subir Sachdev. "Majorana Liquids: The Complete Fractionalization of the Electron." *Physical Review Letters* 105, 057201 (2010). DOI: 10.1103/PhysRevLett.105.057201