Quantum uncertainty helps solve an old problem

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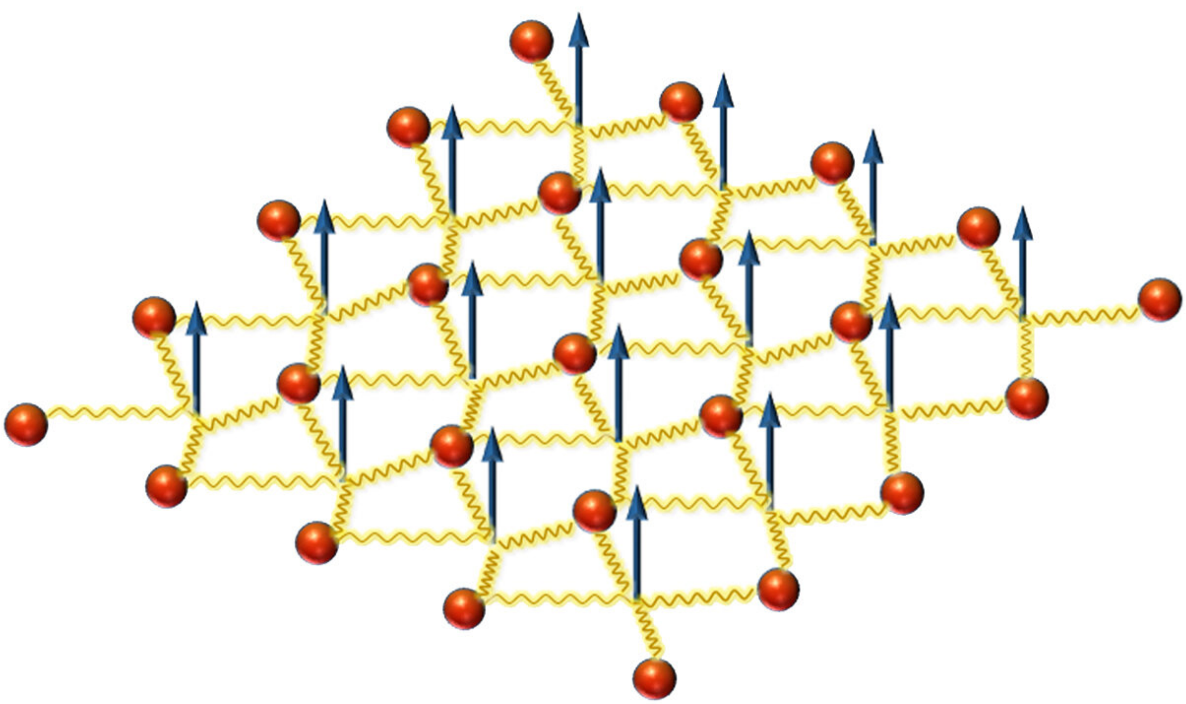

Electrons in a 2D lattice interact with a magnetic field (blue perpendicular arrows), and its quantum fluctuations via the exchange of photons (wiggly yellow lines), which changes how the electrons move through the lattice. Credit: Vasil Rokaj

Controlling how electrons zip through a material is of central importance to build novel electronic devices. How the electronic motion is affected by magnetic fields is an old problem that has not been fully resolved, yet has already led to multiple physics Nobel prizes. Now, researchers at the Max Planck Institute for the Structure and Dynamics of Matter in Hamburg have solved one of the longstanding problems in the field, namely, how a certain symmetry can be restored. Their results were just published in *Physical Review Letters*.

Electrons moving in a strong magnetic field perform a circular motion due to the Lorentz force on which electromagnetic induction and the electric motor are based. In the quantum flatland of atomically thin two-dimensional materials, this leads to weird quantum effects like the integer and the fractional quantized Hall effects, which state that the number of Lorentz-deflected charges are not arbitrary but increase in discrete (quantized) steps.

Despite much progress in the field, the fundamental description of how electrons behave in magnetic fields has remained somewhat incomplete. "There is a deep problem here. Let's say I have a giant magnetic coil and generate a field that is the same everywhere in space .The electrons in my quantum sheet should feel the same force everywhere," says Vasil Rokaj, Ph.D. student in the MPSD Theory Department and lead author of the study. "But standard textbooks treating the magnetic field classically fail to account for this physical requirement," he adds.

With a team of researchers led by MPSD Theory Director Angel Rubio and group leaders Michael Ruggenthaler and Michael Sentef, Rokaj and co-author Markus Penz set out to derive new equations that would resolve this shortcoming. "We did not know originally what to expect," adds Ruggenthaler. "In fact, we were interested in a different problem, namely, how a quantized rather than classical field in a so-called cavity affects the electronic motion."

To achieve this, Rokaj had to use the formalism of quantum electrodynamics, which was first developed in the 1930s and 1940s to describe how electrons and photons interact. When Rokaj wrote down the equations for the electrons in the solid, the team realized that something interesting happened. "The magnetic field in a coil is composed of photons, so in principle, we should be able to also describe the old problem with our new approach," says Ruggenthaler. "Surprisingly, the quantum uncertainty (or fluctuations) of the field, which is usually not taken into account, helps to restore the fundamental symmetry—that everything should be the same no matter where in space we look."

Angel Rubio adds, "These efforts prove that we are on the right track by tackling the problem in a fully quantum way." In his Theory Department, many researchers work on the large-scale problem of how photons change the properties of matter—from novel chemical reactions to materials that might help build future quantum computers. "This work proves that it is always worthwhile to take a fresh look at old problems, and to start from the basic principles," says Rubio. "I am sure that further surprises are just waiting to be discovered."

More information: Vasil Rokaj et al. Quantum Electrodynamical Bloch Theory with Homogeneous Magnetic Fields, *Physical Review Letters* (2019). DOI: 10.1103/PhysRevLett.123.047202

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