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The observation of Bloch ferromagnetism in composite fermions

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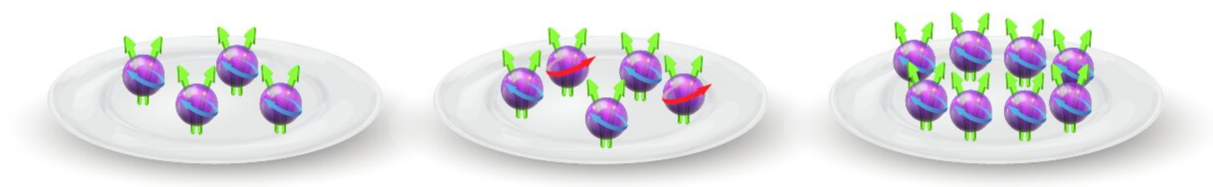


Schematic evolution of the spin polarization of composite fermions as a function of the density. At large densities, the composite fermions are fully spin polarized (all spinning in one direction). As the density is lowered below n = 4.2 × 10^10 cm^-2, the full spin polarization is lost (i.e. some composite fermions are spinning clockwise, and the rest are spinning counterclockwise). At even lower densities n = 3.51× 10^10 cm^-2, however, the composite fermions suddenly become fully spin polarized (all spinning in one direction), signaling a Bloch-like transition. Credit: Md Shafayat Hossain et al.

Composite fermions are exotic quasi-particles found in interacting 2-D fermion systems at relatively large perpendicular magnetic fields. These quasi-particles, which are composed of an electron and two magnetic flux quanta, have often been used to describe a physical phenomenon known as the fractional quantum Hall effect.

Researchers at Princeton University and Pennsylvania State University recently used composite fermions to test a theory introduced by physicist Felix Bloch almost a century ago, suggesting that at very low densities, a paramagnetic Fermi "sea" of electrons should spontaneously transition to a fully magnetized state, which is now referred to as Bloch ferromagnetism. Their paper, published in *Nature Physics*, provides evidence of an abrupt transition to full magnetization that is closely aligned with the state theorized by Bloch.

"Composite fermions are truly remarkable," Mansour Shayegan, professor of Electrical Engineering at Princeton University and one of the researchers who carried out the study, told Phys.org. "They are born of interaction and magnetic flux, and yet they map such a complex system to a simple collection of quasi-particles that to a large degree behave as non-interacting and also behave as if they don't feel the large magnetic field. One of their most interesting properties is their spin polarization."

When strong magnetic fields are applied to them and the Zeeman energy is predominant, composite fermions are known to become fully spin polarized (i.e., fully magnetized). At lower magnetic fields, on the other hand, they are typically only partly magnetized, as the Coulomb energy plays a considerably larger role.

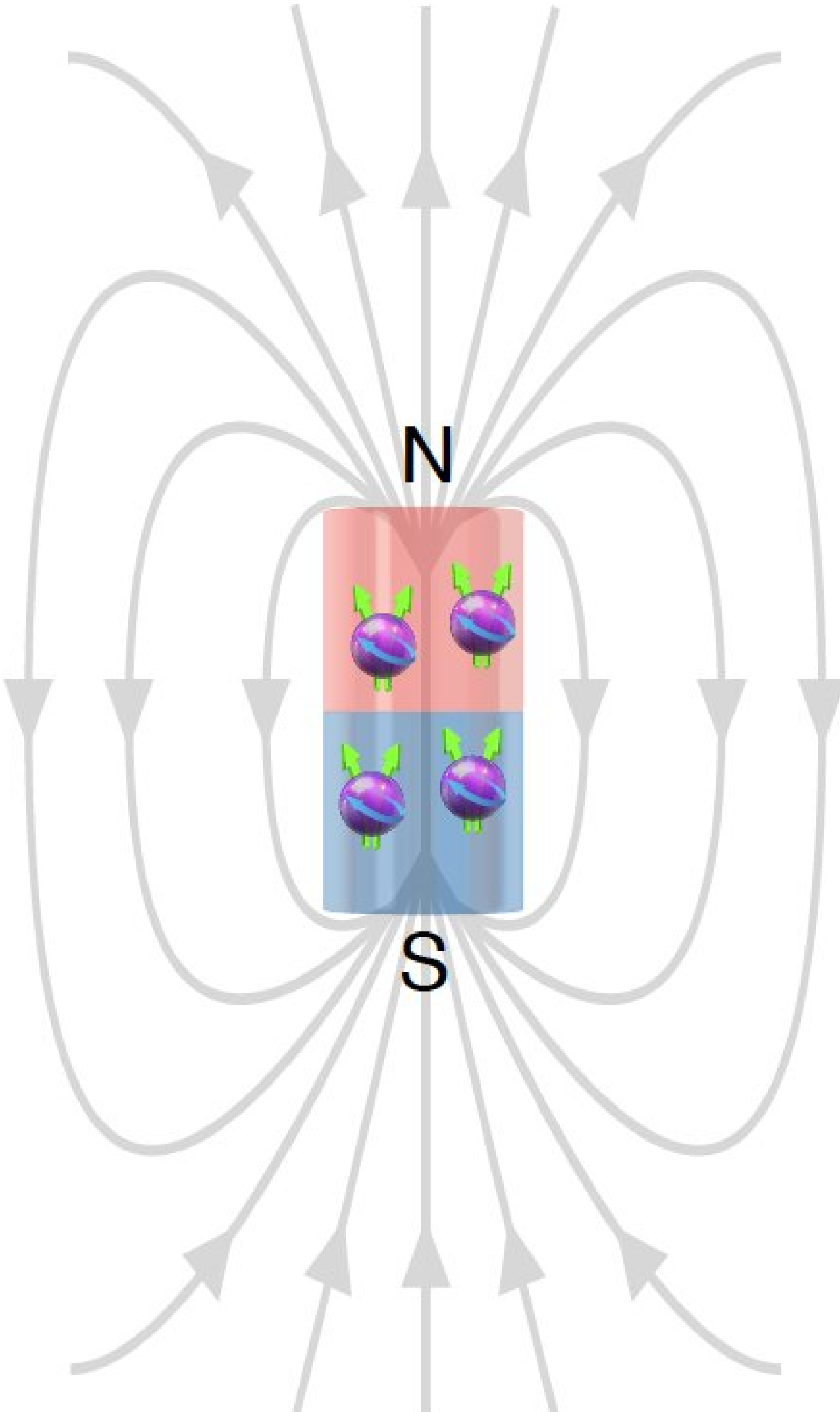
Fascinated by this unique characteristic of composite fermions, Shayegan and his colleagues set out to probe and investigate it further. To do this, they used a technique for directly measuring spin polarization that relies on the ballistic (collision-free) transport of composite fermions over relatively long distances, of the order of 0.2 micron.

"We saw that as we lowered the density of composite fermions (and hence the magnetic field at which they are formed), they indeed lost their full spin polarization, as expected," Shayegan said. "But then came a completely unexpected surprise: As we lowered the density even more, all of a sudden, the composite fermions became fully spin polarized again. We had a hunch that this may be a result of the weak 'residual' interaction between the composite fermions, but we were unable to prove it."

If the phenomenon observed by Shayegan and his team does, in fact, result from the weak residual interactions between different composite fermions, this phenomenon would be highly reminiscent of Bloch ferromagnetism, the state predicted by Bloch in 1929. Remarkably, this effect has so far proved to be very difficult to demonstrate experimentally.

"A key to the success of our experiments was the availability of modulation-doped, gallium-arsenide/aluminum-gallium-arsenide semiconductor structures of extremely high quality," Shayegan said. "These were grown, using molecular beam epitaxy by our Princeton colleague Loren Pfeiffer and his group."

To gain greater insight on whether the phenomenon they observed was actually comparable to Bloch ferromagnetism, Shayegan and his team reached out to Jainendra Jain, a theoretical physicist at Pennsylvania State University. Jain and his students, Tongzhou Zhao and Songyang Pu, carried out a series of calculations aimed at ascertaining the validity of the researchers' hypothesis.



Magnetization of fully-spin-polarized composite fermions at low densities. Credit: Md Shafayat Hossain et al.

"When my Princeton colleagues first told me about their experimental result, it came as a total surprise," Jain said. "The model of free composite fermions works so well for their Fermi sea at the half-filled Landau level, that I did not expect Bloch type physics here; such behavior was certainly not predicted by any existing theory. This is a very complex problem to tackle theoretically, because it relates to very tiny changes in energy as a function of the density."

To gain a theoretical understanding of the phenomenon observed by Shayegan and his team, Jain and his students used a tool known as 'the fixed-phase diffusion Monte Carlo' method. When they applied this theoretical construct to the problem at hand, they found that the ferromagnetic state was predominant below a critical density.

Moreover, Jain and his students found that the critical density value derived from their calculations was close to the value observed by their colleagues at Princeton. Their results thus support the hypothesis that the observed state resembles Bloch ferromagnetism.

"The underlying physics was revealed to be similar to that for electrons at zero magnetic field," Jain explained. "The interaction energy of composite fermions prefers the ferromagnetic state whereas their kinetic energy the paramagnetic state. As the density is lowered, at some point the interaction energy wins, causing a transition into a fully ferromagnetic phase."

Simple systems with interacting electrons are very common and interacting fermions are found in all metals, so these systems have often been the focus of physics studies. Although they have been widely investigated, Bloch ferromagnetism in these systems has not yet been clearly observed.

This team of researchers was among the first to observe an effect that resembles Bloch ferromagnetism. Moreover, they observed this effect in an unusual set of quasi-particles (i.e., a Fermi sea of composite fermions), which was surprising and unexpected.

"The theory of composite fermions is well-established," Md Shafayat Hossain, the lead author of the study, told Phys.org. "Most phenomenology in theory and experiments involving the composite fermions can be understood without any interaction between the composite fermions. Therefore, this is perhaps the last platform where one expects to find signatures of strong interactions. Surprisingly, however, our experiments reveal that the composite fermions undergo Bloch ferromagnetism, which is a prototypical manifestation of strong inter-fermion interaction."

The recent work by Shayegan, Jain, Hossain and their colleagues yielded a number of interesting results, which have important implications both for the study of Bloch ferromagnetism and composite fermions. On one hand, it demonstrates the existence of an interaction-induced transition to ferromagnetism that is aligned with the phenomenon predicted by Bloch in 1929.

On the other hand, the recent paper enhances the current understanding of composite fermions, as it shows that at very low densities these quasi-particles can have strong interactions with each other. In their next studies, the researchers plan to continue searching for Bloch ferromagnetism in fermions, specifically in conditions characterized by zero magnetic field.

"When an electron system is made sufficiently dilute so that the Coulomb energy dominates over the kinetic (Fermi) energy, the electrons should align their spins and become fully magnetized," Shayegan said. "This is the original problem that Bloch, and later on

Edmund Stoner (in 1947), and others discussed; a classic, textbook problem that has eluded experiments. The experimental challenge is to make the electron system very dilute, and yet keep the disorder potential (that competes with the Coulomb interaction and wants to tarp electrons at random sites) to a minimum level. We think with new, modulation-doped electron systems, there is a chance to finally nail down the Bloch transition for zero-field electrons."

More information: Bloch ferromagnetism of composite fermions. *Nature Physics* (2020). DOI: 10.1038/s41567-020-1000-z.