Skyrmions and magnons in the quantum Hall effect in graphene

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As a consequence of the approximate spin-valley symmetry in graphene, in a strong magnetic field, the ground state of electrons in graphene at charge neutrality is a particular SU(4) quantum Hall ferromagnet. If only the Coulomb interaction is taken into account, this ferromagnet can appeal either to the spin degree of freedom or equivalently to the valley pseudo-spin degree of freedom. This freedom in choice is then limited by subleading energy scales that explicitly break the SU(4) symmetry, the simplest of which is given by the Zeeman effect that orients the spin in the direction of the magnetic field. In addition, there are also valley symmetry breaking terms that can arise from short-range interactions or electron-phonon couplings [1]. Here, we build upon the phase diagram of the ground state in order to identify the different skyrmions at filling $\nu=0$ and spin waves at $\nu=\pm1$ that are compatible with these types of quantum-Hall ferromagnets. Similarly to the ferromagnets, the skyrmions at charge neutrality are described by the $\text{Gr}(2,4)$ Grassmannian at the center, which allows us to construct the skyrmion spinors. The different skyrmion types are then obtained by minimizing their energy within a variational approach. We obtain a phase diagram consisting of 12 skyrmion types and show that the different skyrmion types have a clear signature in the local, sublattice-resolved, spin magnetization, which is in principle accessible in scanning-tunneling microscopy and spectroscopy.

In addition to the skyrmions, we also describe the generalized spin waves at $\nu=\pm1$, where one encounters pure spin waves, valley-pseudospin waves as well as more exotic entanglement waves that have a mixed spin-valley character. Most saliently, the SU(4) symmetry-breaking terms do not only yield gaps in the spectra, but under certain circumstances, namely in the case of residual ground-state symmetries, render the originally quadratic (in the wave vector) spin-wave dispersion linear. Several recent experiments have successfully emitted and detected pure spin waves in the graphene quantum Hall ferromagnet and observed their scattering at junctions between regions with different filling factors [2-5].

References

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