Observation of Linked Loops in a Quantum Ferromagnet

Ilya Belopolski [a,b]

[a] RIKEN Center for Emergent Matter Science (CEMS), Wako, Saitama 351-0198, Japan
[b] Laboratory for Topological Quantum Matter and Spectroscopy (B7), Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

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Quantum phases can be classified by topological invariants, which take on discrete values capturing global information about the quantum state. Over the past decades, these invariants have come to play a central role in describing matter, providing the foundation for understanding superfluids, magnets, the quantum Hall effect, topological insulators and Weyl semimetals. In this talk, I will introduce a remarkable linking number (knot theory) invariant associated with loops of electronic band crossings in the mirror-symmetric ferromagnet Co_2MnGa [1-4]. We disentangle this system's rich topological structure through bulk-sensitive soft X-ray and surface-sensitive vacuum ultraviolet angle-resolved photoemission spectroscopy. We directly observe three intertwined degeneracy loops in the bulk Brillouin zone three-torus, T^3, such that each loop links each other loop twice. Through systematic spectroscopic investigation of this linked loop quantum state, we explicitly draw its link diagram and conclude, in analogy with knot theory, that it exhibits linking number (2,2,2), providing a direct experimental determination of the topological invariant. On the sample surface, we further predict and observe Seifert boundary states protected by the bulk linked loops, suggestive of a Seifert bulk-boundary correspondence. Our observation of a quantum loop link motivates the application of knot theory to the exploration of quantum matter.

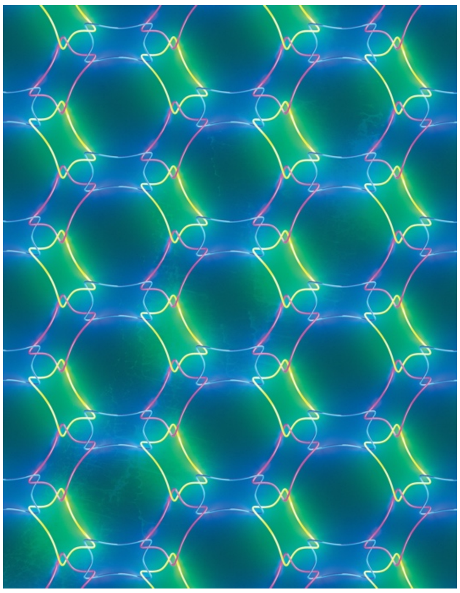

FIGURE 1. Mathematical link diagram in three-dimensional momentum space, characterizing the linking number of the linked Weyl loops (nodal lines) in the quantum ferromagnet Co_2MnGa, as characterized by ARPES.

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