



# Who is the Lord of the Rings in the Zeeman-spin-orbit Saga: Majorana, Dirac or Lifshitz?

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I discuss the simultaneous effects of Zeeman and spin-orbit fields during the evolution from Bardeen-Cooper-Schrieffer (BCS) to Bose-Einstein Condensation (BEC) superfluidity for ultracold fermions. I focus on spin-orbit couplings with equal Rashba and Dresselhaus (ERD) strengths which are realized experimentally, and show that topological phase transitions of the Lifshitz class occur through the emergence of Majorana and/or Dirac fermions as Zeeman and spin-orbit fields are varied. Topological quantum phase transitions in superfluids with non-s-wave order parameters have been conjectured theoretically for p-wave and d-wave systems for many years, but not yet observed experimentally due to the absence of tunable parameters. However, Zeeman or spin-orbit fields and interactions can be tuned in the context of ultra-cold atoms and allow for the visitation of several different phases. For systems with finite ERD spin-orbit coupling, but zero Zeeman fields, the evolution from BCS to BEC superfluidity is only a crossover [1] as the system remains fully gapped. In contrast, for finite Zeeman fields, ERD spin-orbit coupling induces a triplet component in the order parameter that produces nodes in the quasiparticle excitation spectrum leading to bulk topological phase transitions of the Lifshitz type. Additionally, a fully gapped phase exists, where a crossover from indirect to direct gap occurs. For spin-orbit couplings with equal Rashba and Dresselhaus strengths the nodal quasiparticles are Dirac fermions that live at and in the vicinity of rings of nodes. Transitions from and to nodal phases can occur via the emergence of zero-mode Majorana fermions at phase boundaries, where rings of nodes of Dirac fermions annihilate [2]. Furthermore, I characterize different superfluid phases at low temperatures via spectroscopic and thermodynamic properties to conclude that Lifshitz is the “Lord of the Rings” [3], and that crossing the critical temperature of the superfluid as a function of interaction, Zeeman field and spin-orbit coupling can reveal manifestations of such phases at finite temperatures [4].

[1] Li Han, C. A. R. Sá de Melo, “Evolution from BCS to BEC superfluidity in the presence of spin-orbit coupling”, *Physical Review A* **85**, 011606(R) (2012), see also arXiv:1106.3613v1.

[2] Kangjun Seo, Li Han and C. A. R. Sá de Melo, “Topological phase transitions in ultra-cold Fermi superfluids: the evolution from BCS to BEC under artificial spin-orbit fields”, *Physical Review A* **85**, 033601 (2012), see also arXiv:1108.4068v2.

[3] Kangjun Seo, Li Han, and C. A. R. Sá de Melo, “Emergence of Majorana and Dirac particles in ultracold fermions via tunable interactions, spin-orbit effects, and Zeeman fields”, *Physical Review Letters* **109**, 105303 (2012), see also arXiv:1201.0177v1.

[4] Philip D. Powell, Gordon Baym, C. A. R. Sá de Melo, “Superfluid transition temperature of spin-orbit and Rabi coupled fermions with tunable interactions”, arXiv:1709.07042v1.