

Emergence of multiple zero modes bound to vortices in extended topological Josephson junctions

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We study planar Josephson junctions formed on the surface of a three-dimensional topological insulator (Fu-Kane proposal). We examine the experimentally relevant parameter regimes in which the frequently used effective description in terms of two counter-propagating one-dimensional Majorana modes with hybridization dependent on the Josephson phase difference reaches its validity limit. This happens when the effective velocity of the emergent one-dimensional Majorana modes approaches zero. As parameters like the chemical potential or the width of the junction are tuned, instances of vanishing effective velocity mark the emergence of additional ‘Dirac cones’ at zero energy and finite momentum. If the junction is subjected to an external magnetic field, Josephson vortices may then bind a number of zero modes in addition to the topological Majorana mode. The additional zero modes are ‘symmetry-protected’ and can be lifted by a broken mirror symmetry (which is to be expected in realistic scenarios) as well as by an in-plane magnetization (or Zeeman field). We note that the ensuing presence of additional low-energy Andreev states can significantly contribute to measured quantities like the Josephson current or microwave absorption spectra.