Phase Structure of Superconductors Coexisting with Ferromagnetism

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Some materials such as UCoGe are known to support both the p-wave superconducting (SC) order *and* the ferromagnetic (FM) order. These materials have been mainly studied by applying the mean field theory (MFT) to the Ginzburg-Landau (GL) theory in the continuum. However, the minimal coupling between the vector potential for the FM order parameter and the SC order parameter makes a simple MFT approximation assuming, e.g., a constant SC order parameter unreliable for phenomena related to nonuniform field configurations. In this paper, we reformulate the GL theory as a three-dimensional lattice field theory, and study its phase structure and critical behavior nonperburbatively by Monte Carlo simulations. Due to the spatial lattice, topological defects, i.e., vortices, can be generated without cutoff for core singularity. We find a stable SC state in the FM region due to the Zeeman coupling between the FM magnetization of electrons in the normal channel and the "spin" of p-wave SC pairs. Obtained phase diagram has a qualitative resemblance to that of UCoGe in the pressure-temperature plane. We also find that, when the transition temperatrure of FM is lower than that of SC as $T_{\mathrm{FM}}/T_{\mathrm{SC}} < 0.7$, coexisting phase of FM and SC appear only near the surface of the lattice with vortices formed in the central region. This result suggests interesting possibility that in some cases the coexisting phase appears only in the surface of materials such as $ZrZn_2$.