Coherence Lengths and Magnetic Penetration Depth in Multiband Superconductors from Microscopic Calculations

Tristan Ryoma Fuchs[1], Takuya Nomoto[2], Hikaru Watanabe[3], and Ryotaro Arita[1,4]
[1] *Department of Physics, The University of Tokyo, Hongo, Tokyo 113-0033, Japan*
[2] *Department of Physics, Tokyo Metropolitan University, Hachioji 192-0397, Japan*
[3] *Graduate School of Engineering, Hokkaido University, Sapporo 060-8628, Japan*
[4] *Center for Emergent Matter Science, RIKEN, Wako 351-0198, Japan*

Keywords: Coherence length, Magnetic Penetration Depth, Multiband Superconductivity

In multiband superconductors, it is known that multiple coherence lengths originating from different bands can emerge. Such a property gives rise to a variety of physical phenomena that do not appear in single-band systems and is also related to the possibility of so-called type-1.5 superconductivity, in which type-I and type-II characteristics coexist [1]. However, methods for accurately evaluating characteristic length scales, such as coherence lengths and the magnetic penetration depth, for a given multiband superconducting state have not yet been fully established.

In this study, we systematically compare three different computational methods that are applicable to general multiband superconducting systems. The first method focuses on Cooper pairs with finite momentum and evaluates the coherence lengths from the momentum dependence of the order parameters [2]. The second method introduces vortices into a sufficiently large real-space system and evaluates the coherence lengths and magnetic penetration depth from the spatial decay of the order parameters and magnetic field [3]. As a third method, we developed a free-energy-functional approach, in which the coherence lengths and magnetic penetration depth are obtained by analyzing the structure of the superconducting free energy [4].

For these three methods, we compare their numerical stability and the ranges of parameters to which they can be applied. Our comparison shows that the newly developed free-energy-functional approach is particularly useful, since it remains applicable at low temperatures, requires relatively low computational cost, and can be used for both single-band and multiband superconducting systems. These features make it a favorable method among the approaches examined here for evaluating coherence lengths and the magnetic penetration depth.

[1] E. Babaev *et al*., Phys. Rev. B **72**, 180502 (2005); J. Carlström et al., Phys. Rev. B **83**, 174509 (2011).
[2] N. Witt *et al*., npj Quantum Materials **9**, 100 (2024).
[3] Y. Nagai *et al*., J. Phys. Soc. Jpn. **81**, 024710 (2012).
[4] T. R. Fuchs *et al*., arXiv: 2609.06014