

Master 2 Research Internship

Collective modes and pair-density-wave superconductivity in $2H\text{-NbSe}_2$



Supervisor: Prof. Dr. Dirk Manske
Host institution: Max Planck Institute for Solid State Research, Stuttgart, Germany
Research area: Theoretical condensed-matter physics / superconductivity
Duration: 4–5 months
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Scientific background and pair-density-wave scenario

The layered transition-metal dichalcogenide $2H\text{-NbSe}_2$ exhibits coexisting charge-density-wave (CDW) order and superconductivity [1]. Below the superconducting transition, Raman spectroscopy reveals a sharp low-energy excitation traditionally attributed to the superconducting amplitude (Higgs) mode. Its strong Raman visibility is linked to the coupling between superconductivity and the pre-existing CDW order [2]. A long-standing puzzle is that this superconductivity-induced peak is observed in both the A_{1g} and E_{2g} Raman channels, although the conventional Higgs mode of an isotropic s -wave condensate transforms as A_{1g} . Recent theoretical work in our group shows that, in the commensurate $3Q$ state, the residual C_3 rotational symmetry enforces an exact cancellation of the direct Raman–Higgs coupling in the E_{2g} channel. In the real material, CDW incommensurability weakly lifts this selection rule, but explicit calculations show that the resulting spectral weight is too small to account for the observed peak. This motivates the search for a superconducting collective mode intrinsically allowed in the E_{2g} channel. A natural candidate is a pair-density wave (PDW), a superconducting state with finite Cooper-pair momentum [3], for which experimental signatures have been reported in NbSe_2 by scanning Josephson-tunnelling microscopy[4].

Objectives and methods

This project will extend the CDW-superconductivity Raman formalism to finite-momentum pairing. It involves constructing a minimal microscopic model for PDW components, determining PDW symmetry and equilibrium phase structure, and classifying superconducting collective fluctuations under relevant symmetries, particularly in A_{1g} and E_{2g} sectors. The study will calculate Raman susceptibility in these channels to identify PDW collective modes with Raman spectral weight. The goal is to compare the calculated energy, linewidth, and spectral weight of the E_{2g} response with experimental data and the conventional Higgs–CDW mechanism, with the aim of identifying experimental signatures that distinguish these mechanisms. This theoretical condensed-matter physics internship will utilize analytical and numerical methods, including group-theoretical analysis, functional-integral techniques, Gaussian fluctuation theory, collective-mode propagators, and diagrammatic linear-response theory for Raman susceptibility.

Candidate profile

The project is intended for a Master 2 student with a solid background in quantum mechanics and condensed-matter physics. Familiarity with superconductivity, Green’s functions, many-body physics, or linear-response theory would be useful but is not required. The project involves both analytical calculations and numerical work, so a good level of autonomy in these areas is expected.

References

- ¹M.-A. Méasson, Y. Gallais, M. Cazayous, B. Clair, P. Rodière, L. Cario, and A. Sacuto, *Phys. Rev. B* **89**, 060503(R) (2014).
- ²T. Cea and L. Benfatto, *Phys. Rev. B* **90**, 224515 (2014).
- ³D. Shaffer, F. J. Burnell, and R. M. Fernandes, *Phys. Rev. B* **107**, 224516 (2023).
- ⁴X. Liu, Y. X. Chong, R. Sharma, and J. C. S. Davis, *Science* **372**, 1447–1452 (2021).