Swedish-German Wilhelm and Else Heraeus-Seminar 2026: Quantum Condensates and Quantum Geometry (QCQG)

Monday 23 March 2026 - Thursday 26 March 2026

Nordita, Stockholm

Scientific Programme

The advent of highly-controlled atomic-level synthesis of two-dimensional (2D) van-der-Waals heterostructures has opened a wide array of interesting questions on condensation phenomena in a previously unexplored realm. Just as one example, combining materials with intrinsically non-trivial band structures into heterostructures can lead to exotic superconducting phases with unique geometric and topological properties.

The reduced dimensionality also enables unprecedented possibilities to externally tune properties, e.g. by electrostatic gating, or by placing ad-atoms on their surface. Gating single-layered or bilayered materials can lead to strong modification of the intrinsic band structure, and may also strongly affect the superconducting state. In fact, many low-dimensional materials have complex phase diagrams with several competing ordered states at low temperature when carrier doping, pressure, or magnetic field is varied. Often these phases are strongly correlated.

Furthermore, strong intrinsic spin-orbit interactions (e.g. of the Rashba- or Ising-type) stabilize spin-full Cooper pairs that resist extremely large magnetic fields, which has been shown e.g. in monolayers of transition metal dichalcogenides (TMDs). This opens a wide array of possibilities for finding novel superconducting phases in newly synthesized materials and systems. Tailoring band structures and characterizing their topological properties are important new methods, which are framed in the context of quantum geometric concepts.

Quantum geometry has come to play a key role in modern condensed matter physics. On one hand it describes phenomena in which Berry phases lead to quantized quantum transport (for example Thouless pumps, spin pumps, and related phenomena), characterized by topological invariants of the Chern type. On the other hand it defines a quantum metric, measuring the quantum distance between states. Overall, quantum geometry combined with quantum condensates, especially superconductivity, lead to the possibility of an interplay between the condensate phase and the geometry and its associate phases, allowing for additional phase control and fundamentally new types of devices. In fact, for 2D materials with a flat (i.e. non-dispersive) normal band structure, a finite quantum metric is needed to achieve finite supercurrents.

Another interesting aspect are quantum geometric phases associated with non-trivial spin textures. Non-trivial spin textures in combination with superconductivity give rise 1to a complex interplay between spin-singlet and spin-triplet superconducting correlations, allowing for superconducting spintronics. Superconducting spintronics is based on the
spin of the Cooper pair, rather than the spin of the single electron, and combines the advantages of dissipationless transport with spin selectivity and coherence.

Quantum geometry is formally given by the quantum geometric tensor. Its imaginary part is the Berry curvature tensor, while the real part gives the quantum metric. Thus the imaginary part is strongly connected to topology, while the real part connects to concepts such as quantum entropy and entanglement entropy. Ultimately, modern research in these
fields is directed towards a unifying description of concepts of geometry and topology with the physics of coherent quantum transport, quantum dissipation, entanglement, and non-Abelian gauge fields. On the other hand, the classification of superconductors and magnets, with unconventional superconductivity and altermagnetism as prominent current
research topics, is based on the concept of symmetry breaking. Combining geometry, topology, and symmetry breaking, is bound to generate a veritable ocean of possibilities for new and novel physical phenomena.

The growing literature on quantum geometry and its developing central role in condensed matter calls for a return of the rich physics of unconventional superconductivity. Here the interplay of superconducting and spin-degrees of freedom is bound to give rise to nontrivial quantum geometry of the Bogoliubov spectra, i.e. the low-energy excitation spectra of the superconductor. This may occur in either native unconventional superconductors or in engineered van-der Waals materials, where superconductors and magnetic materials are brought in proximity of each other. Here also the discovery of altermagnetism, a third magnetic phase different from ferro- and antiferromagnetism, allows for new possibilities to predict and describe new low-energy states in hybrid systems.