

When Magnetism and Superconductivity Cooperate

Superconductors are materials that can carry electrical current with no energy loss, a property that promises revolutionary technologies – from ultra-efficient power transmission to powerful quantum devices. Most known superconductors, however, work only at extremely low temperatures and under carefully controlled conditions. Understanding why superconductivity emerges and how it can be controlled remains one of the central challenges of modern physics.

This project focuses on a particularly intriguing material: **CeRh₂As₂**, a so-called *heavy-fermion superconductor*. In such materials, electrons behave as if they are hundreds of times heavier than normal, due to strong interactions between them. These interactions give rise to exotic quantum states, where superconductivity, magnetism, and other forms of electronic order compete – or unexpectedly cooperate.

What makes CeRh₂As₂ exceptional is that it does not have just one superconducting state. Instead, experiments have revealed **multiple superconducting phases that can be switched by applying a magnetic field**. Even more puzzling, in a certain range of temperatures, superconductivity can disappear and then *reappear* as the magnetic field is increased. This rare phenomenon is known as *reentrant superconductivity*. This behavior challenges the traditional view that magnetism and superconductivity are always antagonists.

Adding to the mystery is an enigmatic low-temperature phase known as the ***T₀* phase**, which appears just above the superconducting transition. Initially it thought to be a subtle, non-magnetic form of electronic ordering, but growing experimental evidence suggests that this phase has a magnetic character and may coexist with superconductivity. If true, this would overturn long-standing assumptions and point toward a new mechanism in which **magnetism actively reshapes superconductivity instead of destroying it**.

The main goal of this project is to uncover the microscopic origin of the *T₀* phase and to understand how it influences (or perhaps controls) the switching between different superconducting states. To achieve this, we will combine several approaches. First, we will study ultra-pure single crystals of CeRh₂As₂ under extreme conditions (very low temperatures and very strong magnetic fields) using advanced experimental probes that can detect even tiny magnetic signals. Second, we will compare CeRh₂As₂ with closely related materials, helping to identify which features are universal and which are unique among them. Third, we will deliberately modify the material by replacing selected atoms, allowing them to “tune” magnetism and superconductivity in a controlled way.

Beyond solving a specific scientific puzzle, this research aims to verify a **new hypothesis of superconductivity controlled by magnetism**. Such knowledge could eventually guide the design of materials in which superconducting properties can be switched on demand, which is a long-term dream for quantum technologies and energy applications. At the same time, the project will advance crystal-growth techniques.

By revealing how complex quantum states emerge from strongly interacting electrons, this project addresses one of the most fascinating questions in contemporary physics: **how new forms of matter arise when the rules of the quantum world are pushed to their limits**.