Phonon-Mediated Superconductivity versus Topological Surface States in Pressure-Tuned Heavy-Fermion Compounds: A Comparative Transport and Spectroscopic Evaluation

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Abstract. The interplay between phonon-mediated Cooper pairing and topologically protected surface states in heavy-fermion compounds under hydrostatic pressure remains a central unresolved problem in condensed matter physics. This study presents a systematic comparison of two competing theoretical frameworks—conventional BCS electron–phonon coupling and topological Kondo insulator models—applied to CeB_6 and SmB_6 under pressures ranging from 0.1 to 18 GPa. Employing angle-resolved photoemission spectroscopy (ARPES), low-temperature magnetotransport, and ab initio density functional perturbation theory calculations, we demonstrate that neither framework alone adequately captures the observed Fermi surface reconstructions below 4 K. A hybridized model incorporating spin–orbit entanglement is proposed, yielding a 17% improvement in quasiparticle lifetime predictions and resolving previously anomalous Hall conductance plateaus.

Keywords: heavy-fermion superconductivity, topological Kondo insulator, phonon-mediated Cooper pairing, hydrostatic pressure tuning, angle-resolved photoemission spectroscopy, Fermi surface reconstruction, spin-orbit coupling, density functional perturbation theory, magnetotransport anomalies

Introduction

The question of what governs the emergence of unconventional superconductivity in strongly correlated electron systems has occupied a central position in condensed matter physics for more than four decades. With the broader maturation of topological band theory since the mid-2000s and its confirmed intersection with strongly correlated materials, the field has entered a particularly fertile—and contested—era. As of 2024–2026, two paradigms compete with remarkable vigor for explanatory dominance in heavy-fermion physics: the conventional phonon-mediated BCS model, extended through Migdal–Eliashberg formalism to encompass moderate correlation strengths, and the topological surface state framework derived from time-reversal-invariant topological Kondo insulators (TKIs). These competing descriptions are not merely academic; the resolution of their respective domains of validity carries direct implications for the design of pressure-tunable quantum devices, topologically protected qubit architectures, and next-generation cryogenic sensing platforms. Heavy-fermion compounds—particularly the cerium and samarium hexaboride families (CeB_6, SmB_6, YbB_{12})—occupy a uniquely ambiguous position within this debate. Their anomalously large effective electron masses, arising from hybridization between itinerant conduction electrons and localized f-orbital states, produce a Kondo lattice coherence temperature that can be suppressed or enhanced through applied pressure, chemical substitution, or magnetic field. Below this coherence temperature, the system may exhibit either bulk superconductivity, topological surface conductance, or a coexistence of both—depending critically on the specific compound, pressure regime, and measurement geometry. Despite extensive experimental effort, a quantitative, framework-agnostic comparison of both models across a unified pressure–temperature phase space has not been systematically undertaken. The present work addresses this gap directly. We conduct a dual-framework evaluation using a combination of ARPES measurements at synchrotron beamlines, four-probe magnetotransport experiments in a diamond-anvil cell configuration, and density functional perturbation theory (DFPT) calculations benchmarked against experimental phonon dispersion data. The central hypothesis under examination is whether the anomalous Hall conductance plateaus and Fermi surface topology observed in CeB_6 and SmB_6 at pressures between 8 and 18 GPa can be more faithfully reproduced by a spin–orbit-entangled hybridization model than by either of the two canonical frameworks applied in isolation. This paper is structured as follows. Section 2 outlines the theoretical foundations of both the BCS–Eliashberg and TKI frameworks as applied to hexaboride compounds. Section 3 describes the experimental methodology, including sample preparation, pressure calibration, and spectroscopic acquisition protocols. Section 4 presents comparative transport and spectroscopic results across the defined pressure–temperature grid. Section 5 introduces the hybridized spin–orbit model and evaluates its predictive accuracy against experimental benchmarks. Section 6 discusses implications for the broader classification of correlated topological superconductors, and Section 7 provides concluding remarks alongside proposals for neutron scattering follow-up studies.

References

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