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Strongly correlated electron phenomena in filled skutterudites

M. Brian Maple
Department of Physics and Institute for Pure and Applied Physical Sciences
University of California, San Diego
La Jolla, CA 92093 USA
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The filled skutterudite compounds MT_4X_{12} (M = alkali metal, alkaline earth, lanthanide, actinide; T = Fe, Ru, Os; X = P, As, Sb) display a wide variety of strongly correlated electron phenomena and are candidates for thermoelectric applications. The strongly correlated electron phenomena include conventional BCS superconductivity, unconventional superconductivity, magnetic order, quadrupolar order, valence fluctuation behavior, heavy fermion behavior, non-Fermi liquid behavior, and hybridization gap semiconductor (Kondo insulator) behavior. When M is a lanthanide or actinide atom, the localized f-states hybridize with the ligand-states of the surrounding pnictogen atoms that form atomic ÒcagesÓ within which the M atoms reside. The ground states are determined by a delicate interplay between the hybridization of the f- and ligand-states, crystalline electric field splitting of the f-electron energy levels, magnetic and quadrupolar interactions, and electron band structure. Examples of the strongly correlated electron phenomena found in filled skutterudite compounds are reviewed in this talk. The examples will primarily be drawn from recent experiments on single crystals of ternary La-, Ce-, and Pr-based filled skutterudite arsenides and antimonides LnT_4X_{12} (Ln = La, Ce, Pr; T = Fe, Ru, Os; X = As, Sb) and pseudoternary Pr-based skutterudite antimonides $Pr(Os_{1-x}Ru_x)_4Sb_{12}$ and $Pr_{1-x}Nd_xOs_4Sb_{12}$. For example, $CeOs_4As_{12}$ was found to be a Kondo insulator, while $CeRu_4As_{12}$ was observed to display non-Fermi liquid behavior. The compounds PrT_4As_{12} were found to exhibit ferromagnetic order below 18 K for T = Fe, BCS superconductivity below 2.4 K for T = Ru, and an unknown type of order and antiferromagnetic order below 2.3 K and 2.2 K, respectively, for T = Os. The temperature and field dependences of the specific heat and electrical resistivity indicate that $PrOs_4As_{12}$ is a Kondo lattice system with a small Kondo temperature T_K of 1 K and an electronic specific heat coefficient of 1 J/mol K^2. The T-x phase diagrams of $Pr(Os_{1-x}Ru_x)_4Sb_{12}$ and $Pr_{1-x}Nd_xOs_4Sb_{12}$ reveal regions of superconductivity with different order parameter symmetry and magnetic order. This research was supported by the U.S. Department of Energy (DOE) under Grant Number DE-FG02-04ER46105, the National Nuclear Security Administration (NNSA) under the Stewardship Science Academic Alliance Program through the U.S. DOE under Grant Number DE-FG52-06NA26205, and the U.S. National Science Foundation under Grant Number DMR0802478.