Physica C 514 (2015) 246–278

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Unconventional superconductivity in heavy-fermion compounds

B.D. White [a,b], J.D. Thompson [c], M.B. Maple [a,b,*]

[a] Department of Physics, University of California, San Diego, La Jolla, CA 92093, USA
[b] Center for Advanced Nanoscience, University of California, San Diego, La Jolla, CA 92093, USA
[c] Los Alamos National Laboratory, Los Alamos, NM 87545, USA

ARTICLE INFO

Article history:
Received 16 January 2015
Received in revised form 17 February 2015
Accepted 19 February 2015
Available online 27 February 2015

Keywords:
Unconventional superconductivity
Heavy-fermion behavior
Quantum critical point
Non-Fermi liquid behavior
Magnetic fluctuations
Kondo lattice

ABSTRACT

Over the past 35 years, research on unconventional superconductivity in heavy-fermion systems has evolved from the surprising observations of unprecedented superconducting properties in compounds that convention dictated should not superconduct at all to performing explorations of rich phase spaces in which the delicate interplay between competing ground states appears to support emergent superconducting states. In this article, we review the current understanding of superconductivity in heavy-fermion compounds and identify a set of characteristics that is common to their unconventional superconducting states. These core properties are compared with those of other classes of unconventional superconductors such as the cuprates and iron-based superconductors. We conclude by speculating on the prospects for future research in this field and how new advances might contribute towards resolving the long-standing mystery of how unconventional superconductivity works.

Contents

* Corresponding author at: Department of Physics, University of California, San Diego, La Jolla, CA 92093, USA.
E-mail address: mbmaple@ucsd.edu (M.B. Maple).

http://dx.doi.org/10.1016/j.physc.2015.02.044
0921-4534/

1. Introduction

In the two decades prior to the 1979 discovery of unconventional superconductivity in $CeCu_2Si_2$ [1], the properties of superconductors were typically studied within the context of the Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity [2–4]. The BCS theory describes pairing between conduction electrons as being mediated by phonons so that the characteristic Debye temperature, Θ_D, plays an important role as an energy scale. However, the unexpected discovery of superconductivity in $CeCu_2Si_2$ turned this paradigm on its head. The superconducting Cooper pairs in $CeCu_2Si_2$ are not formed from ordinary conduction electrons, but are rather composed of quasiparticles with enhanced effective masses [1]. Furthermore, the hierarchy of energy scales departs significantly from what is assumed in the BCS theory, indicating that pairing of the quasiparticles cannot be phonon-mediated. These observations made it clear that $CeCu_2Si_2$ was no ordinary superconductor, and heralded a new era of research on unconventional superconductivity. The course of this research has evolved into current explorations of rich phase spaces wherein new and exciting physics has emerged from tuning the delicate interplay between competing ground states. Before discussing the unconventional superconducting states in these fascinating materials, which is the subject of this review, we first briefly introduce the characteristics and origin of heavy-fermion compounds.

1.1. Heavy-fermion compounds

The physical properties of simple metals such as the elements sodium or copper can be understood well by models that neglect the many-body interactions that occur between electrons. In even slightly more complex materials, this unrealistic assumption fails dramatically, but the itinerant electron states and their interactions with other electrons can be transformed into non-interacting quasiparticles with enhanced effective masses by invoking the Fermi liquid theory [5–7]. A Fermi liquid state, which is populated by these independent quasiparticles, is characterized by properties that include a quadratic temperature dependence of the electrical resistivity, $\rho(T) \sim (T/T_F)^2$ for $T \ll T_F$, where $T_F = \epsilon_F/k_B$ is the Fermi temperature and ϵ_F is the Fermi energy [8]. Such a quadratic temperature dependence was first experimentally resolved in 1975 by Andres et al. in measurements on the compound $CeAl_3$ [9]. While T_F values for simple metals such as copper are of order 10^4 K [10] and a $(T/T_F)^2$ temperature dependence of ρ is very difficult to resolve experimentally, analysis of $\rho(T)$ and other physical properties indicated that T_F was three orders of magnitude lower (i.e., 15–25 K) in $CeAl_3$ [9]! Furthermore, T_F is inversely proportional to the coefficient of the electronic contribution to specific heat, γ, which is proportional to the electronic density of states at $\epsilon_F, \mathcal{N}(\epsilon_F)$, and is roughly 0.7 mJ mol^{-1} K^{-2} for copper [10] compared to $\gamma \simeq 1600$ mJ mol^{-1} K^{-2} for $CeAl_3$ [9]. Instead of observing magnetic order within the lattice of localized magnetic moments associated with trivalent Ce ions separated by $\sim$4 Å, a nonmagnetic Fermi-liquid ground state, populated by quasiparticles of order 1000 times heavier than free electrons, was observed in $CeAl_3$. These astounding results hinted at an enormous increase in $\mathcal{N}(\epsilon_F)$ as well as the emergence of a new characteristic energy scale in $CeAl_3$ that acts as an effective T_F.

To understand how these remarkable properties are possible, it is instructive to first consider what happens when a single impurity bearing a localized magnetic moment is dissolved into a non-magnetic metallic host. The Friedel–Anderson model was developed principally to explain magnetic moment formation in metals, but it also describes such a single-ion impurity scenario [11]. In this model, quantum mechanical admixing or hybridization between the localized electron states of the impurity ion and the itinerant electron states from the host, characterized by hybridization matrix element $\mathcal{V}$, produces a virtual bound state or resonance in the density of electronic states with width $\Gamma \propto \mathcal{V}^2$ [11]. When the energy associated with this resonance (the maximum) is within Γ of $\epsilon_F, \mathcal{N}(\epsilon_F)$ is enhanced.

Addressing a different problem (at least superficially), Jun Kondo proposed a simple Hamiltonian to explain the logarithmic divergence with decreasing temperature observed since the 1930s [12] in measurements of $\rho(T)$ on systems containing dilute magnetic impurities. The essential physics of the Kondo Hamiltonian is embodied in a magnetic exchange coupling $\mathcal{J}$ between the spin $\vec{S}$ of a magnetic impurity with the local spin density of the surrounding conduction electrons $\vec{s_0}$. Using this model and the second Born approximation [13], Kondo was able to derive the long sought after $\rho(T) \sim -\log(T)$ behavior. More importantly for our discussion, a new energy scale, designated the Kondo temperature T_K, also emerged from these calculations [13], which separates the temperature region over which the calculations are valid $(T > T_K)$ from $T < T_K$ where perturbation theory breaks down. The Friedel–Anderson and Kondo models, which contribute an enhancement of $\mathcal{N}(\epsilon_F)$ and a new energy scale T_K, respectively, are equivalent descriptions of a magnetic impurity in a metallic host as shown by Schrieffer and Wolff [14]. The antiferromagnetic exchange interaction of the Kondo model $\mathcal{J}$ is calculable in terms of $\mathcal{V}$ from the Friedel–Anderson Hamiltonian,

$$\mathcal{J} = 2\mathcal{V}^2(1/|\epsilon_f| + 1/(\epsilon_f + U)), \tag{1}$$

where $\epsilon_f = \epsilon_i - \epsilon_F$ and ϵ_i is the energy of the localized electrons in the unfilled shell of the magnetic impurity ion [14].

A physical picture of how a magnetic impurity interacts with its surroundings emerges from these theoretical developments. At temperatures comparable to but greater than $T_K \propto \exp[-1/(\mathcal{N}(\epsilon_F)\mathcal{J})]$ [15], the antiferromagnetic exchange interaction, characterized by $\mathcal{J}$, between $\vec{S}$ and $\vec{s_0}$ promotes polarizing $\vec{s_0}$ antiparallel to the direction of $\vec{S}$. This tendency causes the localized magnetic moment of the impurity ion to become dynamically screened or compensated, and the exchange interaction leads to strong local spin-flip or incoherent Kondo scattering of charge carriers (i.e., a $\rho(T) \propto -\log(T)$ term is obtained in this temperature