Magnetic field induced rotation of the d-vector in Sr$_2$RuO$_4$

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Abstract

The superconductor Sr$_2$RuO$_4$ is widely believed to be a spin triplet system with a chiral order parameter analogous to the A phase of superfluid helium-3. The best evidence for this pairing state is that the Knight shift or spin susceptibility measured in neutron scattering is constant below $T_c$, unlike in a spin-singlet superconductor. The original Knight shift and neutron scattering measurements were performed for magnetic fields aligned in the ruthenate a-b plane. These would be consistent with a triplet d-vector $d(\vec{k})$ aligned along the c-axis. However recently the Knight shift for fields along c was also found to be constant below $T_c$, which is not expected for this symmetry state. In this paper we show that while spin-orbit interaction stabilises the c-axis oriented d-vector, it is possible that only a very small external B field may be sufficient to rotate the d-vector into the a-b plane. In this case the triplet pairing model remains valid. We discuss characteristics of the transition and the prospects to detect it in thermodynamic quantities.

Key words:
ruthenate superconductors, pairing symmetry, d-vector rotation
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1. Introduction

Strontium ruthenate is an intriguing low $T_c$ superconductor [1]. It is widely believed to have spin triplet order parameter. The orbital symmetry of it, however, is still unknown. Knight shift [2] and spin susceptibility [3] being constant below $T_c$ point to the chiral state with d-vector $d(\vec{k}) \sim (k_x + ik_y)\hat{e}_z$. This state (called (a) in the following) is also consistent with the $\mu$-SR experiments which show spontaneous time reversal symmetry breaking at $T_c$ [4]. It was recently confirmed in phase sensitive experiments [5].

The original Knight shift measurements were performed for magnetic fields aligned in the ruthenate a-b plane. Recently the Knight shift [6] has been measured in magnetic field parallel to the c-axis. In contradiction to expectations it was found that the susceptibility is also unchanged from the normal state value below $T_c$. It was noted [6] that this result would be consistent with the assumption that the d vector rotates away from the $\hat{e}_z$ direction under the influence of the external field. However a simple rotated state, such as $d(\vec{k}) \sim (k_x + ik_y)\hat{e}_z$, is not allowed in tetragonal symmetry. Instead, the symmetry allowed states $d(\vec{k}) = (\sin k_x, \sin k_y, 0)$ and $d(\vec{k}) = (\sin k_y, -\sin k_x, 0)$ (which below we refer to as (b) and (c) respectively) would also explain the data as the spin susceptibility for either of these states is of the form [7]

$$\hat{\chi}_s(T) = (\chi_n/2)\text{diag} \left( 1 + Y(T), 1 + Y(T), 2 \right),$$

(1)

corresponding to a constant spin susceptibility for c-axis fields consistent with the results of Murakawa et al. [6].

It is the purpose of this work to study in some
detail the scenario of d-vector rotation in the c-axis magnetic field. Specifically, we shall study the possible effect of the weak external (Zeeman only) magnetic field on the symmetry of the lowest energy pairing state.

To this end we use a recently proposed [8] phenomenological three-band, three dimensional model with a realistic band structure [8]. It takes into account the three ruthenium $t_{2g}$ orbitals $xz, yz$ and $xy$. The hopping integrals $t_{mnv}(ij)$ for orbitals $m$ and $m'$ and Ru sites $i$ and $j$ as well as the site energies $\varepsilon_m$ are fitted to reproduce the experimentally determined Fermi surface [9]. The effective spin and orbital dependent attractive Hubbard parameters $U_{mn}^{\alpha\beta,\gamma\delta}(ij)$ are chosen to give correct transition temperatures. Without spin - orbit coupling the model with only two values of interaction parameters: an in - plane $U_\parallel = U$ and out - of - plane $U_\perp$ results in the chiral state (a), as the ground state of the system.

2. Results

For spin-independent interactions the alternative pairing states (b) and (c) are the ground state for any value of $\lambda > 0$. To get the state (a) as the ground state in the presence of non-zero spin-orbit interaction $\lambda$ one has to take into account that the spin-orbit coupling leads to a small spin dependence of the effective pairing interaction [10]. Choosing $U_\parallel' \equiv U_{\parallel}^{\uparrow\downarrow}$ about 1% larger than $U \equiv U_{\parallel}^{\uparrow\uparrow} = U_{\downarrow\downarrow}$ is sufficient to stabilize the chiral state even for large spin orbit coupling. In Fig. 1 we show the free energies of the (a), (b) and (c) symmetry pairing states as a function of external magnetic field $H \parallel c$. The model parameters were chosen to make the chiral state (a) stable at zero field. One can see that the chiral phase increases its free energy as the field is increased, until at a certain critical field the (b) or (c) solutions become more stable. Therefore we expect a “spin flop” type phase transition from a d-vector oriented along the c-axis to one where the d-vector lies in the a – b plane. A similar rotation is observed in the bulk superfluid state of $^3$He-A where the d-vector rotates continuously to remain perpendicular to the applied field [11].

In the case of Sr$_2$RuO$_4$ the transition is not simply a rotation of the chiral d-vector but is also a transition from a chiral to non-chiral pairing state of different symmetry. The two distinct solutions shown in Fig. 1 (note that (b) and (c) are essentially degenerate) have different entropies, as shown in the figure inset, and hence this Freericksz-like [11] spin-flop is a first order thermodynamic phase transition. It has not yet been observed, because the specific heat jump at this transition is very small in comparison with the main jump at 1.5K, as our (unpublished) calculations indicate.

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