ONE HUMP OR TWO? STONER'S CAMEL AS A MODEL OF UGe_2*

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We present a model of changing Fermi surface geometry in a ferromagnetic, spin-split environment, where the control parameter is the Stoner exchange energy. A two-peak density of states, here obtained from a quasi-one-dimensional bandstructure allows two jumps in magnetisation. The jump at finite magnetisation can be first order, and may occur near a maximum in the transition temperature for a triplet superconducting instability. Our motivation is the ferromagnetic superconductor, UGe_2.

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1. Introduction

Increasingly frequently, superconductivity is being observed in the region where the temperature of a magnetic phase transition is pushed to zero [1]. One such recent, and extremely novel example of this has been the discovery (under hydrostatic pressure) of superconductivity in UGe_2, a weak itinerant ferromagnet [2]. The surprises have been twofold — firstly the appearance of 'ferromagnetic superconductivity' — the coexistence of itinerant electron ferromagnetism (FM) and superconductivity (SC) — and secondly the apparent absence of SC in the paramagnetic regime, at pressures beyond the critical pressure, $p_{\rm c}$. This is seen in figure 1(a) where we show the temperature-pressure phase diagram of UGe_2. The Curie temperature $T_{\rm C}$ and superconducting transition temperature $T_{\rm SC}$ are indicated [2, 8, 9]. Another feature, T_x is also shown. This T_x shows up in various thermodynamic,

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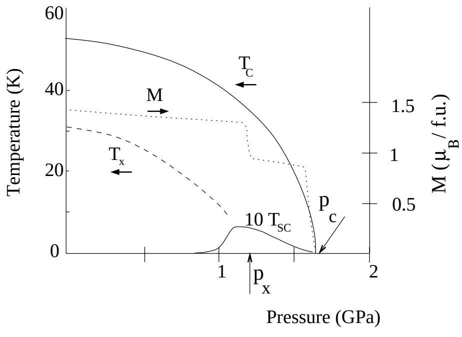

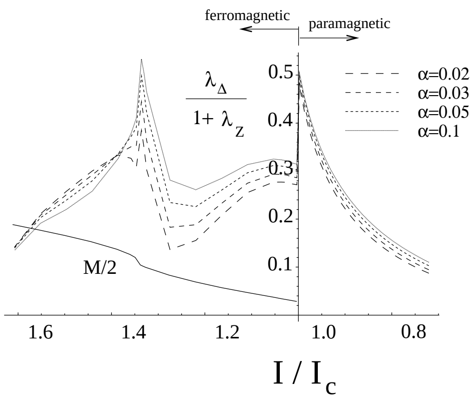

Fig. 1. (a) The temperature-pressure phase diagram [2,8,9] of UGe_2. T_{SC} is the superconducting transition temperature, scaled by a factor of 10 for clarity. T_C denotes the Curie temperature. The low temperature magnetisation, M, shows two first order steps, one at p_c and the other at p_x (after [10]). The feature at p_x is the zero temperature extrapolation of the T_x line (see text). (b) Calculated measure of the strength of superconductivity as a function of Stoner interaction strength, I, normalised with respect to I_c, the value of I at the zero temperature Curie point. I_x, the value of I for the second jump in magnetisation, akin to the pressure identified as p_x in UGe_2, gives rise to the peak at $I_x/I_c \sim 1.34$. We show results for different values of 'Stoner structure factor', α. To guide the eye, scaled down, calculated zero temperature magnetisation is shown in dimensionless units.

and transport measurements [2,9,11,12] and as a slight jump in magnetisation, M [9] which is sharpened at lower temperatures (as also shown). The close proximity of the peak in T_{SC} and T_x in the phase diagram is suggestive: if T_x was the magnetic transition responsible for enhancing SC in this system, we could perhaps put UGe_2 in a familiar class of quantum critical magnetic superconductors [1].

As they stand, theoretical models do not account for the observed phase diagram, as a consequence of considering a three-dimensional system, either magnetically isotropic [3] or uniaxial [4]. Where an enhancement of T_{SC} within the FM state has been predicted, the basis for this seems unjustified in the case of UGe_2, either on grounds of magnetic anisotropy [5] or for the lack of any observed charge density wave fluctuations [6]. A Hund's rule exchange model has been proposed [7] for the coexistence of FM and SC, but this does not provide an explanation for T_x.

Thus there is no consistent model for T_x and the enhancement of (triplet) pairing within the ferromagnetic state. We present such an model, the key ingredient being an electronic density of states (DOS) with two peaks.

2. Model

We consider the action of pressure to be akin to that of varying the exchange energy, I in a conventional Stoner Model of the one-electron energy of separated majority and minority spin sheets [13]. We fix the total number of spins, N and allow the total energy density of the electron system (kinetic plus exchange energies) to include a term for the presence of an external magnetic field. The Stoner model is considered inadequate at finite temperatures, especially for isotropic ferromagnets. We therefore restrict ourselves to working with a uniaxial model (which is a good approximation in UGe_2 [14]) at zero temperature.

Most phenomenological expansions of this energy density have included terms even in M, up to order M^6 (ie cubic in M^2). This can give one first order transition in M. We need to model two transitions, both possibly first order [10] and thus we assume a camel-shaped, two-hump DOS which can generically bring about an M^8 term in the free energy [15]. This DOS will arise from assuming a quasi-one-dimensional tight-binding dispersion, and we choose to focus on $\epsilon(\boldsymbol{k}) = -\cos k_x(1 + 0.7\cos k_y) - 0.03\cos 2k_x + 0.03\cos 3k_x$, which is highly one-dimensional and contains strong nesting at saturation magnetisation, in line with bandstructure calculations on UGe_2 [16, 17]. In our search for triplet pairing, we will utilise the interaction potential for spin fluctuation mediated pairing in the ferromagnetic state, as derived by Fay and Appel [3]. Rather than display an estimate of T_{SC}, which is complex when the interaction potential is highly temperature-dependent, we will examine the ratio of interaction and mass renormalisation parameters, $\lambda_\Delta/(1+\lambda_Z)$, defined as in Ref. [18]. The choice of order parameter should naturally reflect the symmetry properties of the UGe_2 crystal structure. Such considerations should lead us to examine non-unitary states, [19, 20] but here for simplicity we consider as an example the states $\Delta_{\boldsymbol{k}} = \Delta_0 \sin(k_x)$ and $\Delta_0 \sin(k_y)$. We calculate all $\chi^{(0)}_{\sigma\sigma}(\boldsymbol{q})$ at a small finite temperature and introduce a 'Stoner structure parameter', α, to convey some of the physics of electron-electron interactions at finite distances. Thus, $I \to I/(1 + \alpha q^2)$.

3. Results

Fuller details of the results are contained elsewhere [15]. For two first order transitions in $M(I)$, we require under half-filling of the band in the paramagnetic state, although this condition is not sufficient. We use $N = 0.77$ in what follows. It has been found that the features associated with T_x can be recovered at pressures above p_x by the application of a magnetic field. This metamagnetism is a natural consequence of our model.

The measure of superconducting interaction strength is shown in Figure 1(b) for various values of α, our Stoner 'structure factor'. What is important is the stable region of superconductivity in the ferromagnetic state, where $\frac{\lambda_\Delta}{1+\lambda_Z}$ can be approximately flat. Furthermore, in the region between $I_{\rm c}$ and I_x, the mass renormalisation, represented by λ_Z is also approximately flat and high. This mass enhancement compares well with recent de Haas van Alphen measurements on the ferromagnetic state between pressures $p_{\rm c}$ and p_x, where the measured effective mass seems to remain high [11].

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