Existence of the FFLO State in Superconducting UPd_2Al_3

In a recent Letter, Gloos *et al.* [1] have suggested that the heavy fermion superconductor UPd_2Al_3 has a transition in magnetic field from the normal state to an inhomogeneous superconducting state, known as the FFLO state [2], followed at lower fields by a first order phase transition to the usual flux lattice state, with the phase lines meeting at $T/T_c = 0.8$ where T_c is the zero field transition temperature. To investigate this, the author derives a formula for the upper critical field for the FFLO state valid at all temperatures in the clean limit and shows that the ratio T/T_c for a type II superconductor is less than the value 0.55 found previously for a type I superconductor. Fits to the UPd_2Al_3 data indicate that this ratio should be either zero or considerably less than 0.55. This result brings into question a FFLO interpretation of the data.

The derivation of H_{c2} follows that of WHH [3]. The FFLO state is obtained by multiplying the usual eigenvector of the Gor'kov equations at H_{c2} by e^{iQz}. Using an analogous procedure as WHH, the T_c equation is

$$\ln\left(\frac{T_{c0}}{T_c}\right) = 2\sum_{n=0}^{\infty}\left[\frac{1}{2n+1} - \mathrm{Re}(I_n)\right], \tag{1}$$

where

$$I_n = \frac{2\pi T_c e^{\eta^2}}{v_F\sqrt{\hbar eH/2c}}\int_{\eta}^{\infty} dw\, e^{-w^2}\frac{1}{2i}\ln\left(\frac{1+i\alpha_n w}{1-i\alpha_n w}\right), \tag{2}$$

and $\alpha_n = v_F\sqrt{\hbar eH/2c}/(\omega_n + id)$ with v_F the Fermi velocity, $\omega_n = (2n+1)\pi T_c$, $d = g\mu_B H/2$, and g the g factor. The quantity η is $Q\sqrt{\hbar c/2eH}$ and is chosen to maximize H_{c2} for a given T. The results of these equations match the zero temperature curves presented by Gruenberg and Gunther [4].

The parameters used for UPd_2Al_3 are $T_{c0} = 2$ K, $v_F = 1.2\times10^4$ m/sec, and $g = 2$, with v_F being fit to give the experimental upper critical field slope at zero field of 4.2 T/K [1]. Figure 1 shows the low temperature behavior of H_{c2} for both zero Q and nonzero Q. The zero temperature H_{c2} is considerably lower than the experimental value of 3.5 T. Moreover, the FFLO state does not exist for $T/T_c > 0.15$, whereas the experimental phase lines are split up to $T/T_c = 0.8$. One can fit H_{c2} to the experimental value of 3.5 T by decreasing g to 1.5, but no FFLO state is found in that case. Another possible fit is to increase T_{c0} as suggested by Gloos *et al.* [1], the idea being that the actual T_c at zero field is somewhat suppressed over its bare value by pair breaking from the antiferromagnetism. This is demonstrated by the other set of points in Fig. 1, where a T_{c0} of 2.3 K has been fit to give an H_{c2} of 3.5 T. Even for this case, the FFLO state does not exist for $T/T_c > 0.25$, compared to the experimental value of 0.8.

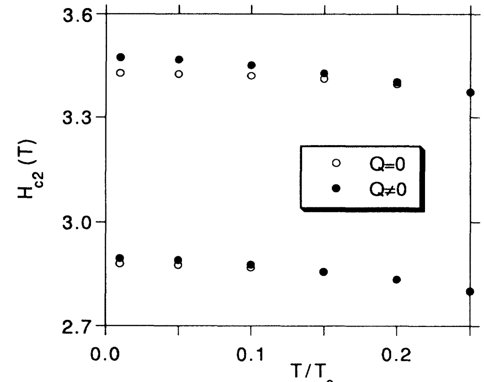

FIG. 1. Calculated H_{c2} vs T/T_c for UPd_2Al_3. The lower set of points is for $T_{c0} = 2$ K, the upper set for $T_{c0} = 2.3$ K.

There are two possibilities left. Either the scenario put forth in Ref. [1] is incorrect or a different inhomogeneous solution is occurring. If one generalizes Q to a vector, then one of the form (Q_x, iQ_x, Q_z) also satisfies Eq. (1) with the same T_c. To obtain a different result, one must break cylindrical symmetry (this could be caused by the antiferromagnetism as suggested in Ref. [1]). In that case, though, the Abrikosov solution is no longer valid. To obtain the more general solution would require rederiving Eq. (1) with a spatially dependent field, a challenging problem not yet solved. It is unlikely, though, that such a solution would exist above the limit of $T/T_c = 0.55$ found for the FFLO state in the type I case.

This work was supported by U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

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Received 8 March 1993
PACS numbers: 74.25.Ld, 74.70.Tx

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0031-9007/93/71(20)/3391(1)$06.00