



## UvA-DARE (Digital Academic Repository)

### Evolution of Magnetism and its Interplay with Superconductivity in Heavy-Fermion $U(\text{Pt},\text{Pd})_3$

Keizer, R.J.

**Publication date**  
1999

[Link to publication](#)

#### **Citation for published version (APA):**

Keizer, R. J. (1999). *Evolution of Magnetism and its Interplay with Superconductivity in Heavy-Fermion  $U(\text{Pt},\text{Pd})_3$* . Universiteit van Amsterdam.

#### **General rights**

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

#### **Disclaimer/Complaints regulations**

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: <https://uba.uva.nl/en/contact>, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

# Appendix I

## E-model: sixth order correction

The low-temperature properties of  $\text{UPT}_3$  are determined by both the antiferromagnetic and the superconducting order parameters. The total free energy with respect to the normal state consists therefore of three components:

$$F = F_M + F_S + F_{MS} \quad (\text{I.1})$$

Here  $F_M$  and  $F_S$  describe the antiferromagnetic and the superconducting contributions and  $F_{MS}$  is the coupling term of the antiferromagnetic and the superconducting order parameters. In the E-model the free energy of the superconducting state is expanded in terms of a vector order parameter,  $\eta = (\eta_x, \eta_y) = (|\eta_x| e^{i\phi_x}, |\eta_y| e^{i\phi_y})$ , describing the complex components of a 2-dimensional gap function ( $E_{1g}, E_{2g}, E_{1u}, E_{2u}$ ). The degeneracy of the components of the superconducting vector order parameter is lifted by a symmetry breaking field ( $\epsilon$ ). With the antiferromagnetic order as the symmetry breaking field  $\epsilon = \gamma m^2$ . In section 3.2.5.2 the fourth order expansion of the free energy is given. There exist four independent sixth-order terms (e.g.  $|\eta|^6, |\eta^3|^2, |\eta^2 \eta^*|^2, |\eta^2|^2 |\eta|^2$ ). We performed calculations adding one sixth order term,  $\delta |\eta|^6/3$ , to the free energy. In order to minimise the total free energy it is written in the components  $|\eta_x|^2$  and  $|\eta_y|^2$ :

$$F = F_M + \alpha_S \left( |\eta_x|^2 + |\eta_y|^2 \right) + \frac{1}{2} \beta_S \left( |\eta_x|^4 + |\eta_y|^4 \right) + \beta_\phi |\eta_x|^2 |\eta_y|^2 + \frac{\delta}{3} \left( |\eta_x|^6 + |\eta_y|^6 \right) + \delta |\eta_x|^2 |\eta_y|^2 \left( |\eta_x|^2 + |\eta_y|^2 \right) - \epsilon \left( |\eta_x|^2 - |\eta_y|^2 \right) \quad (\text{I.2})$$

Here  $\alpha_S = \alpha_{S_0} (T - T_c)$ ,  $\beta_S = \beta_1 + \beta_2$ ,  $\beta_\phi = \beta_1 + \beta_2 \cos(2(\phi_x - \phi_y))$  and  $\alpha_{S_0}$ ,  $\beta_1$  and  $\beta_2$  are the Ginzburg-Landau coefficients which are positive in the superconducting state. By minimising the free energy with respect to  $|\eta_x|$ ,  $|\eta_y|$ ,  $m$  and  $\phi_x - \phi_y$ , one obtains four coupled equations for the equilibrium state. The magnetic term is assumed to be constant in the superconducting state, because the moment is nearly saturated and  $\phi_x - \phi_y = \pi/2$ . There are two coupled equations for the equilibrium state:

$$\begin{aligned}
2|\eta_x| \left[ \alpha_- + \beta_S |\eta_x|^2 + \beta_\phi |\eta_y|^2 + \delta \left( |\eta_x|^4 + |\eta_y|^4 + 2|\eta_x|^2 |\eta_y|^2 \right) \right] &= 0 \\
2|\eta_y| \left[ \alpha_+ + \beta_S |\eta_y|^2 + \beta_\phi |\eta_x|^2 + \delta \left( |\eta_x|^4 + |\eta_y|^4 + 2|\eta_x|^2 |\eta_y|^2 \right) \right] &= 0
\end{aligned} \tag{I.3}$$

Here  $\alpha_{\pm} = \alpha_S \pm \epsilon$ . The two superconducting phases are expressed through normalised order parameter components. The phases are the (1,0) phase with only  $|\eta_x|$  different from zero and the (1, $\alpha$ i) phase where both amplitudes are nonzero and have a relative phase  $\phi_x - \phi_y = \pi/2$ . A double superconducting transition is found for  $\beta_1, \beta_2, \gamma > 0$  with the following solutions:

$$(1,0) \text{ phase: } T_c^+ = T_c + \frac{\epsilon}{\alpha_{S_0}} \tag{I.4}$$

$$\left. \begin{aligned}
|\eta_x|^2 &= \frac{-\beta_S + \sqrt{\beta_S^2 - 4\delta\alpha_-}}{2\delta} \\
|\eta_y|^2 &= 0
\end{aligned} \right\} T_c^- < T < T_c^+ \tag{I.5}$$

$$(1,\alpha i) \text{ phase: } T_c^- = T_c - \frac{\beta_1}{\beta_2} \frac{\epsilon}{\alpha_{S_0}} - \frac{\epsilon^2 \delta}{\alpha_{S_0} \beta_2^2} \tag{I.6}$$

$$\left. \begin{aligned}
|\eta_x|^2 &= \left( \frac{\epsilon}{2\beta_2} - \frac{\beta_1}{4\delta} \right) + \frac{1}{4\delta} \sqrt{\beta_1^2 - 4\delta\alpha_S} \\
|\eta_y|^2 &= -\left( \frac{\epsilon}{2\beta_2} + \frac{\beta_1}{4\delta} \right) + \frac{1}{4\delta} \sqrt{\beta_1^2 - 4\delta\alpha_S}
\end{aligned} \right\} T < T_c^- \tag{I.7}$$

$$\Delta T_c = T_c^+ - T_c^- = \frac{\epsilon}{\alpha_{S_0}} \left( 1 + \frac{\beta_1}{\beta_2} + \frac{\epsilon\delta}{\beta_2^2} \right) \tag{I.8}$$

In the limit of  $\delta \rightarrow 0$ , all equations are the same as in the fourth order E-model. The temperature dependence of the specific heat divided by temperature is derived from the free energy by  $c/T = -\partial^2 F / \partial T^2$ . The results for some reasonable values of the coefficients are plotted in section 3.2.5.2 figure 3.2. The analytical calculation of  $c/T$  from the free energy is straight forward, but tedious. As a check we performed the calculation both analytically and numerically. The analytical expression is given by:

$$\begin{aligned}
\Delta_{NA} c(T) / T &= \frac{\alpha_{S_0}^2}{\sqrt{\beta_S^2 - 4\delta\alpha_-}} \\
\Delta_{NB} c(T) / T &= \frac{\alpha_{S_0}^2}{\sqrt{\beta_1^2 - 4\delta\alpha_S}}
\end{aligned} \tag{I.9}$$