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STATIC SCALING IN HEAVY FERMIONS

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The usual assumptions of critical scaling near a transition at T_c lead, when T_c is negative, to solutions which are acceptable thermodynamically and seem appropriate to describe physical situations such as heavy fermions. Illustrations are given with the specific heats of UBe_{13} and UPt_3.

The standard theory of continous phase transitions expresses the Gibbs potential of N interacting particles of moment μ as that of $N/n \sim (\xi/\xi_0)^{-d}$ independent particles of size ξ in dimension d and of moment $\mu_{eff} = \mu(\xi/\xi_0)^{d-u} (u \le d)$ so that [1,2]

$$G/T \sim \xi^{-d} g(\xi^{d-u}\eta) \quad \text{where} \quad \eta = H/T. \tag{1}$$

The static scaling hypothesis states that the coherence length ξ is an analytical function of the reduced interaction $K = J/T$ which diverges like

$$(\xi/\xi_0)^d = [(K_c - K)/K_c]^{-\theta/T_c} = (1 - T_c/T)^{-\theta/T_c} \tag{2}$$

when K reaches by lower values a convergence radius K_c which defines T_c. We have introduced the parameter θ

$$\theta/T_c = d\nu = 2 - \alpha = \gamma + 2\beta \tag{3}$$

instead of the usual exponent ν. Differentiating G with respect to T we have for $\eta = o$

$$\mathcal{S} = \delta G/\delta T \sim (1 + (\theta - T_c)/T)(1 - T_c/T)^{\theta/T_c - 1}, \tag{4}$$

$$C_p T^2 = T^3 \delta\mathcal{S}/\delta T = A(1 - T_c/T)^{\theta/T_c - 2}. \tag{5}$$

In order to maintain the entropy finite it is required that $T_c \le \theta$ which is therefore the highest value of the Curie temperature which is compatible with the scaling hypothesis. This condition imposes that $\alpha < 1$ for all transitions where $T_c > 0$. There is no thermodynamic rule which prohibits that $T_c = -T_k$ where $T_k > 0$. Then ξ diverges like a power of the temperature: when $T \to 0$ we have $\xi/\xi_0 = (1 + T_k/T)^{\theta/T_k}$ and

$$\mathcal{S}/(R \ln(2S+1)) = (1 + (\theta + T_k)/T)(1 + T_k/T)^{-1-\theta/T_k}, \tag{6}$$

$$C_p T^2/(R \ln(2S+1)) = \theta(\theta + T_k)(1 + T_k/T)^{-2-\theta/T_k} = f(\theta, T_k) \tag{7}$$

which becomes a Schottky anomaly $C_p T^2/(R \ln(2S+1)) = \theta^2 \exp - (\theta/T)$ when T_k tends to zero.

We have evaluated the amplitude of the coefficient A which factorizes the specific heat in eq. (5) by imposing that the total entropy $\mathcal{S}(T=\infty) - \mathcal{S}(T=0) = R \ln(2S+1)$. This is possible if $T_c < 0$ as the formula remains analytic down to $T = 0$. This leaves only two parameters θ and T_k which can be determined from the knowledge of two points or from the knowledge of e.g. $C_p(T_{max})$ at T_{max} where the specific heat is maximum. We find that $T_{max} = \theta/2$ and

$$C_p(T_{max})/(R \ln(2S+1)) = 4(1 + T_k/\theta)(1 + 2T_k/\theta)^{-2-\theta/T_k} \tag{8}$$

which is represented in fig. 1.

From the knowledge of $C_p(T_{max}) = 2$ J/mol K at $T_{max} = 10$ K in $CeRu_2Si_2$ we deduced $\theta = 20$ K

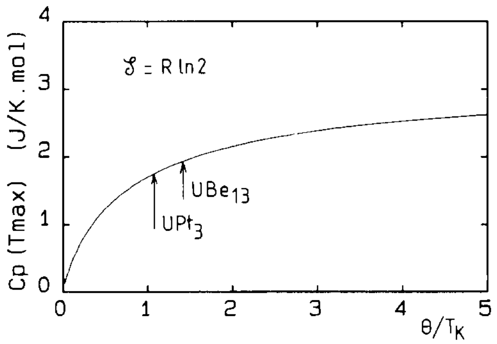

Fig. 1. The amplitude $C_p(T_{max})$ of the specific heat at $T_{max} = \theta/2$ when it is maximum is shown vs. θ/T_k for a total entropy $\mathcal{S} = R \ln 2$. The arrows point to θ/T_k values appropriate for UBe_{13} and UPt_3.

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and $T_k = 13.3$ K from the plot of fig. 1. With these values we could account for the specific heat data within better than 5%. Similar results were obtained with $CeCu_6$ and $CePd_3B_x$ [1,2] supporting the conjecture that the case $T_c < 0$ is well adapted to describe heavy fermions. In general we have found that eq. (6) could give a much better account of the data than the available theories. Admittedly though, as any scaling theory the model does not contain a microscopical information. Also it does not solve a number of difficulties which are also difficulties for the available theories. For example the fig. 2 shows our data in UBe_{13} between 0.4 and 1.2 K in a field of 8 T which was applied to suppress superconductivity [3]. The normal specific heat appeared to be field independent up to these values. The data were adjusted around 1 K with those of ref. [4] which involved that our results should be multiplied by a factor 1.11. The specific heat between 0.2 and 17 K is compared in the fig. 3 with the predictions of eq. (8) which we used twice to fit both the low temperature data and the residual Schottky-like tail. We found $C_pT^2/(R \ln 2) \sim 0.75 f(\theta_1, T_{k1}) + f(\theta_2, T_{k2})$ where $f(\theta T_k)$ is defined in eq. (7) and where $\theta_1 = 2T_{max} = 5.8$ K with $T_{k1} = 4.1$ K and $\theta_2 = 46$ K with $T_{k2} = 4.5$ K. The problem is the factor 3/4 which is necessary to adjust the actual $C_p(T_{max})$ value to that which is expected from fig. 1 for the same best value of the $T_k/\theta \sim 4/3$ ratio. This means that we find only an entropy of $0.75R \ln 2$ below the theoretical curve. We have not the same problem with the high temperature residual tail which announces a first Schottky-like anomaly with entropy $R \ln 2$ and $T_{max} \sim 23$ K.

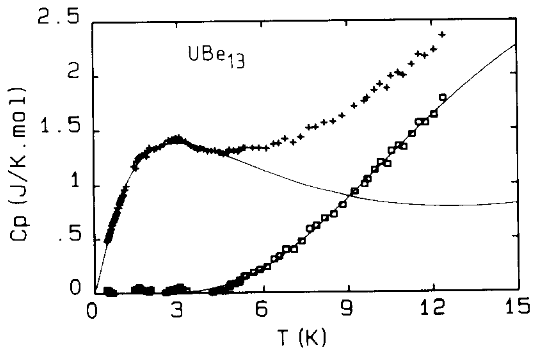

Fig. 2. Below 15 K the normal specific heat of UBe_{13} is the sum of two anomalies each of which is fitted by eq. (7) with $\theta, T_k = 5.8$, 4.1 and 46, 4.5 K, respectively. A T^3 phonon contribution with coefficient 1.05×10^{-4} J/K^4 mol is included in the lower anomaly. The data are from reference [4] and from ref. [3] ($T < 1.2$ K, $H = 8$ T).

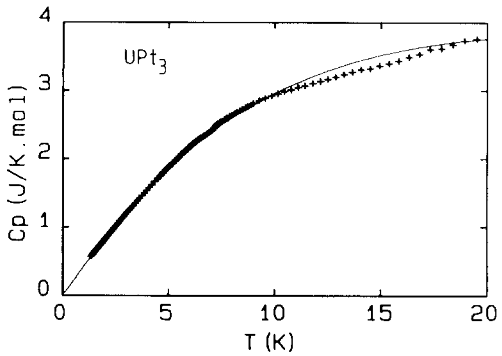

Fig. 3. The specific heat of UPt_3 [5] is well represented by eq. (7). The details of the curve however suggest that it is the sum of two slightly shifted contributions each with entropy $R \ln 2$.

Fig. 3 shows our data in UPt_3 between 2 and 20 K [5] and the theory for $\theta = 2T_{max} = 46$ K [6] with $\theta/T_k = 1.08$. The fit looks satisfactory but it corresponds to a total entropy $2R \ln 2$ and does not account for the detail of the evolution around 16 K which suggests that we may have two slightly shifted contributions.

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