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Scaling in heavy fermions: the case of $CeRu_2Si_2$

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Abstract. — A recently proposed scaling theory of heavy fermions is used to analyze experimental results on $CeRu_2Si_2$ under external applied pressure. We examine susceptibility and resistivity data up to approximately 8 kbars, to obtain relations between the exponents characterizing the quantum critical behavior of this system due to its proximity to a zero temperature magnetic instability.

The Kondo lattice is a model Hamiltonian which has been used successfully to describe the magnetic degrees of freedom of systems which show a competition between Kondo effect and long range magnetic order [1]. This model gives a very good qualitative description of the phenomena occurring in heavy fermions where this competition is the dominant feature. The Kondo lattice Hamiltonian has two parameters J and W which stand for the coupling between conduction electrons and localized moments and the bandwidth respectively. The phase diagram of this model has been investigated by several authors [1, 2] and the main result which comes out from this analysis is the existence of a critical ratio $(J/W)_c$ at zero temperature which separates a phase with long range magnetic order from a non-magnetic one for $J/W > (J/W)_c$ where the Kondo effect dominates. Renormalization group approaches to this problem [2] have shown that this continuous transition is associated with an unstable fixed point at zero temperature ($T = 0$) and $(J/W) = (J/W)_c$. Recently a scaling theory of the Kondo lattice has been proposed [3] which makes use of the properties of this zero temperature fixed point. An interesting feature of this approach is to show unambiguously the existence of a new temperature scale T_c, lower than the single ion Kondo temperature T_K, which is characteristic of the lattice. This temperature or line, in the non-critical part of the $T/W \times J/W$ phase diagram, marks the onset of the Fermi liquid regime and has been associated with the so called coherence transition observed in heavy fermions (Fig. 1). This is a crossover line and its collective or "lattice" character is evidenced by the fact that it is governed by the same exponent of the critical, Neel line, which occurs for $(J/W) < (J/W)_c$.

The scaling theory makes explicit predictions for the scaling behavior of different physical quantities close to the zero temperature transition [3]. We find:

$$f \propto |j|^{2-\alpha} f_F \left[T/T_c \,,\; H/H_c\right] \tag{1a}$$

$$\chi \propto |j|^{-\gamma} f_s[T/T_c\,,\ H/H_c] \tag{1b}$$

$$m_T \propto \gamma = C/T = |j|^{2-\alpha-2\nu z} f_c[T/T_c\,,\ H/H_c] \tag{1c}$$

$$\tau \propto |j|^{-\nu z} f_t[T/T_c\,,\ H/H_c] \tag{1d}$$

$$\xi \propto |j|^{-\nu} f_L[T/T_c\,,\ H/H_c] \tag{1e}$$

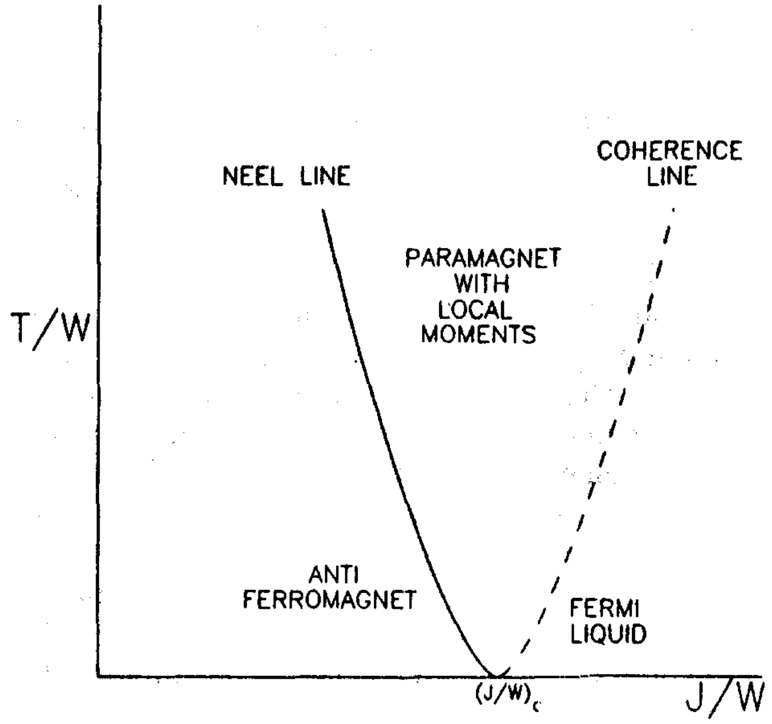

Fig. 1. — Phase diagram of the Kondo lattice. The critical Neel line is governed by the same exponent of the coherence line.

where T is the temperature and H the external field coupled to the order parameter. Since most of the heavy fermions are close to an antiferromagnetic instability, H is a staggered magnetic field. The crossover or coherence temperature $T_c = A|j|^{\nu z}$ and the crossover field $H_c = B|j|^{\beta+\gamma}$. In the equations above, f, χ, m_T stand for the free energy density, the order parameter susceptibility and the thermal mass obtained from the coefficient of the linear term of the specific heat respectively. τ is the characteristic relaxation time which governs the critical slowing down and ξ the correlation length which can be measured by neutron scattering. The reduced variable j is given by $j = (J/W) - (J/W)_c$. Differently from previous approaches to the Kondo lattice where a unique, single ion, energy scale controls all the action [4], we have now a set of critical exponents governing the critical behavior of the system and in particular the enhancement of the susceptibility and of the thermal mass. The exponents α, β, γ, ν, z are standard critical exponents associated with the zero temperature fixed point at $(J/W)_c$ and obey usual scaling laws as $\alpha + 2\beta + \gamma = 2$. However due to the quantum character of the critical fluctuations at a zero temperature transition the dynamic exponent z plays a distinct role [3]. In fact in the scaling laws which involve the dimensionality d it is replaced by $d + z$ so that $d_{\text{eff}} = d + z$ acts as an effective dimensionality [3]. In particular the hyperscaling relation is modified and we have $\nu(d+z) = 2 - \alpha$. This result has important implications as we discuss below. We remark that the characteristic field H_c and the coherence temperature T_c represent crossover values and are not critical parameters. Also we recall that the critical behavior along the Neel line is not governed by the zero temperature fixed point since temperature is a relevant "field". Consequently the exponents along this line are different from those considered here [5]. The generalized scaling theory [6] predicts however that the critical Neel line rises in temperature with the same exponent $(1/\nu z)$ of the coherence line (see Fig. 1). Finally notice that the Fermi liquid regime attained below the coherence line T_c implies that for $T \ll T_c$, $H = 0$, the scaling functions f_x are expanded as $f_x\,[T/T_c] \cong \left[1 + a\,(T/T_c)^2 + b\,(T/T_c)^4 + ..\right]$ and assume for $T = 0$ constant values.

Since the ratio (J/W) depends on the volume of the system, pressure P is an implicit variable in the equations above and can be used to explore the phase diagram of the Kondo lattice [7, 8]. It also allows to check scaling relations predicted by these equations as for example that the susceptibility χ, normalized by its value at a maximum (or its limiting Pauli value), will show universal behavior as a function of pressure i.e., $\chi(T, P)/\chi\,[T_c(P)] = g\,[T/T_c(P)]$. This type of scaling has in fact been observed [8] in $CeRu_2Si_2$. Finally it can be easily shown from equations (1) that maxima, minima or inflection points that occur in the quantities given by these equations as a function of temperature or field will always occur at the characteristic temperature or field and this allows to obtain T_c and H_c experimentally.

Let us consider a given physical quantity X, like the staggered susceptibility or the thermal mass, which close to the zero temperature transition has it's enhancement characterized by an exponent x i.e. $X \propto |j|^{-x} = |(J/W) - (J/W)_c|^{-x}$. For the ratio J/W we assume a dependence on the volume V which is given by $J/W = (J/W)_0 \exp\left[-q\,(V - V_0)\,/V_0\right]$ where $(J/W)_0$ is the value of this ratio at the equilibrium volume V_0 and q a parameter [9]. The Gruneisen parameter [10] Γ_x associated with the physical quantity X, can be easily obtained and is given by:

$$\Gamma_x = \frac{\partial \text{Ln}\, X}{\partial \text{Ln}\, V} = \frac{-qx}{1 - (J/W)_c/(J/W)_0} \tag{2}$$

This equation shows that if the system is close to the magnetic instability such that $(J/W)_0 \cong (J/W)_c$, the Gruneisen parameters may become very large. This is indeed the case in heavy fermions where the large Gruneisen parameters lead to an extreme sensitivity of these systems to changes in the volume and consequently to applied pressure [10]. Another interesting aspect of equation (2) is to show that the ratio between Gruneisen parameters of different quantities, for the same material, allows to obtain relations between the exponents characterizing their critical behavior. In order to make explicit the connection between the Gruneisen parameters and the applied pressure P, we introduce the compressibility $\kappa = (-1/V)\partial V/\partial P$ to obtain

$\Gamma_x = (-1/\kappa)\partial \mathrm{Ln} X/\partial P$. For a more direct comparison of the scaling theory with experiments under applied pressure it is convenient to consider the following expansion for small applied pressures:

$$\mathrm{Ln}\, X(P) = \mathrm{Ln}\, X(0) + \left.\frac{\partial \mathrm{Ln}\, X}{\partial P}\right|_{V=V_0} P \tag{3}$$

from which we get $\mathrm{Ln}[X(P)/X(0)] = -x\,(\kappa_0\Gamma)\,P$, where κ_0 is the equilibrium compressibility and Γ a "property independent" Gruneisen parameter defined as $\Gamma = |\partial \mathrm{Ln}\ j/\partial \ln V|$ such that $\Gamma_x = -x\Gamma$ ($x > 0$). The linear behavior of the logarithm of the normalized pressure variation of a given quantity with applied pressure, for small pressures [8], is illustrated in figure 2 for different properties of $CeRu_2Si_2$. For a given material the product $\kappa_0\Gamma$ is a constant so that the slopes of the lines defined by the data in figure 2 are related to the critical exponent x_i. In particular the pressure variation of the quantities shown in this figure fall on the same line indicating that the exponents governing their behavior assume, within experimental accuracy, the same numerical values. The quantities whose pressure variation are shown in figure 2 are :

i) The normalized temperature of the maxima of the uniform, low field, susceptibility χ_0 at different pressures [8] i.e. $T_c(P)/T_c(0)$. These maxima occur at the coherence temperature T_c characterized by the exponent νz.

ii) The normalized coefficients $[A(0)/A(P)]^{1/2}$ of the T^2 term of the resistivity defined by $\rho - \rho_0 = A\,T^2$ where ρ_0 is the residual resistivity [8, 11]. For the Fermi liquid at $T \ll T_c$, we expect that $A \propto T_c^{-2}$, where T_c is the coherence temperature.

iii) The normalized characteristic uniform field $h_c(P)/h_c(0)$ at which the uniform differential susceptibility $\chi_h = \mathrm{d}M/\mathrm{d}h$ has a maximum [10] for a fixed temperature $T \ll T_c$.

iv) The normalized value of the uniform differential susceptibility [10] at the characteristic uniform field h_c for fixed $T \ll T_c$, i.e. $\chi_h\,(h = h_c,\ T,\ P = 0)\,/\chi_h\,(h = h_c,\ T,\ P)$.

v) The normalized, uniform, low field $(h \ll h_c)$, susceptibility [8] χ_0 at the coherence temperature, i.e. $\chi_0\,(h \cong 0,\ T = T_c,\ P = 0)\,/\chi_0\,(h \cong 0,\ T = T_c,\ P)$.

The system $CeRu_2Si_2$, as evidenced by doping [12] (or negative applied pressure) *is close to an antiferromagnetic instability* and consequently the relevant field coupled to the order parameter and which appears in the scaling functions given in equations (1) is the staggered magnetic field H and not the uniform field h. In order to obtain scaling relations for the uniform susceptibility, we consider a uniform magnetic field and introduce this quantity as a variable scaling close to the zero temperature fixed point as $h' = b^{\sigma} h$ or $(h/J)' = b^{\sigma+z}(h/J)$ where b is a scaling factor. σ is a new exponent and z the dynamical critical exponent which renormalizes the coupling J at the $T = 0$ fixed point [3]. The normalized uniform magnetic field h/J is taken as a relevant field $(\sigma + z > 0)$ implying a multicritical character for the zero temperature fixed point at $(j = 0,\ h/J = 0,\ T/J = 0)$. The relevance of the magnetic field is evidenced by the decrease of the uniform susceptibility under pressure and yields the following scaling expression for the total ground state energy as a function of the uniform magnetic field [3]:

$$f \propto |j|^{2-\alpha} f_h\left[(h/J)/|j|^{\phi_h}\right] \tag{4}$$

where $\phi_h = \nu(\sigma + z)$. Defining a uniform characteristic magnetic field $h_c \propto (J - J_c)^{\phi_h}$ we notice that the uniform field will enter the scaling functions in the combination (h/h_c). We can now derive the scaling form of the uniform susceptibility. We find that the uniform differential susceptibility $\chi_h \propto \partial^2 f/\partial h^2 \propto |j|^{2-\alpha-2\phi_h} f_h(T/T_c, h/h_c)$ and the uniform low field, susceptibility $\chi_0 \propto |j|^{2-\alpha-2\phi_h} f_0(T/T_c)$. Note that the normalized pressure variations of $\chi_h(h = h_c, T)$ and $\chi_0(T = T_c)$ are governed by the same exponents. Then it is a direct consequence of the scaling approach that, independent of the values of the exponents, the susceptibility ratios defined in iv) and v) will present the same variation under applied pressure as shown in figure 2.

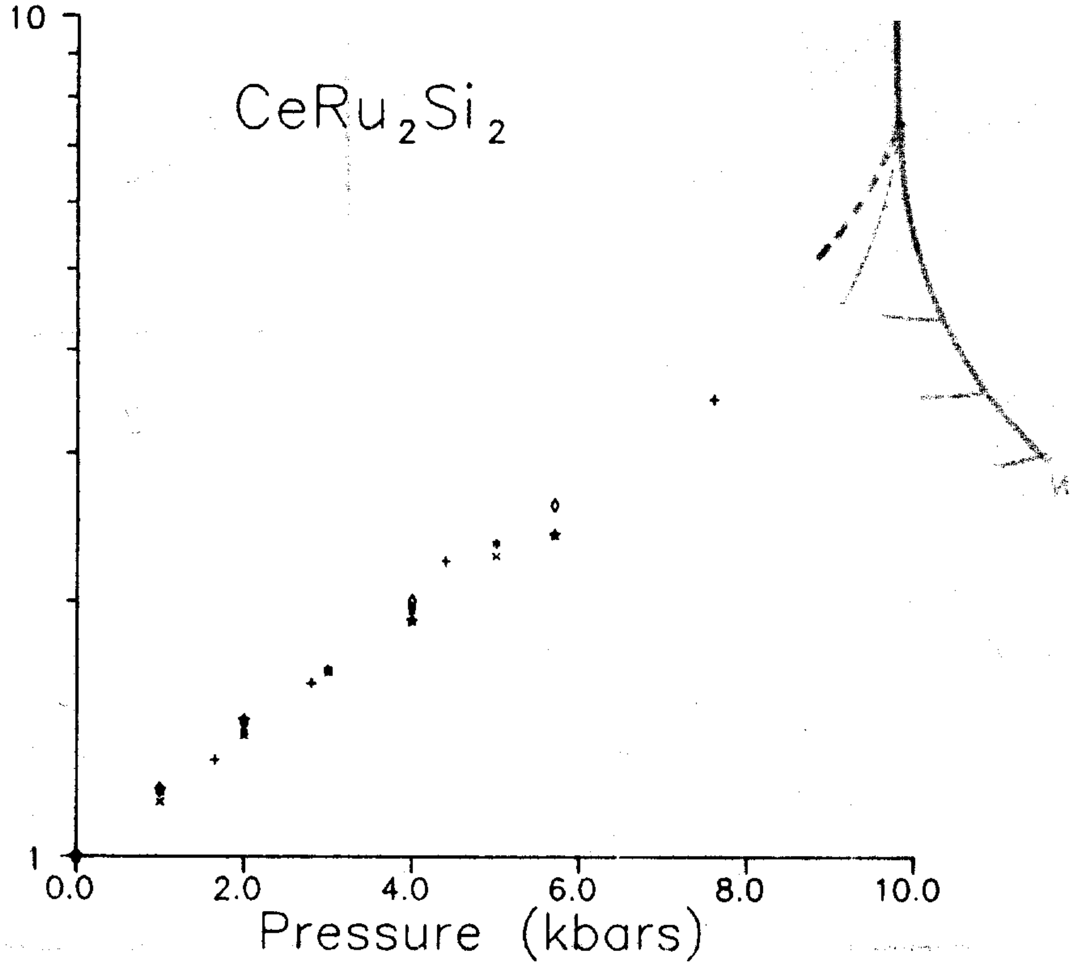

Fig. 2. — Pressure dependence of: $(*)$ $h_c(P)/h_c(0)$; $(\times)$ $\chi_h(h_c, P = 0)/\chi_h(h_c, P)$ for $T \ll T_c$; $(+)$ $[A(0)/A(P)]^{1/2}$; $(\star)$ $T_c(P)/T_c(0)$; $(\diamond)$ $\chi_0(T_c, p = 0)/\chi_0(T_c, P)$ for $h \ll h_c$. For details see text.

The same behavior under pressure is also expected for $[A(0)/A(P)]^{1/2}$ and $T_c(P)/T_c(0)$ as indeed is found in figure 2. This just confirms the Fermi liquid nature of the state attained by CeRu$_2$Si$_2$ at very low temperatures ($T \ll T_c$) i.e. below the coherence line.

A quantitative discussion of the exponents implied by the results shown in figure 2 requires a knowledge of the universality class of the Kondo lattice instability in CeRu$_2$Si$_2$. There are two main points to consider and which will prove very useful in the determination of these exponents. The first concerns the nature of the antiferromagnetic state obtained by doping CeRu$_2$Si$_2$. The Ising character of these systems due to the large anisotropy and strong in-plane correlations [12] suggest that these materials behave as metamagnets whose phase diagram is illustrated in figure 3.

Notice that the $T = 0$ transition in a finite uniform magnetic field is first order and also the presence of a tricritical point. On the other hand the transition line in the $h = 0, T/W \times J/W$ plane is second order as obtained previously [1]. These results suggest the generalized Kondo lattice phase diagram shown in the same figure and make clear the multicritical character of the fixed point at $T/J = 0$, $J/W = (J/W)_c, h/J = 0$ which we will assume behaves as a tricritical point [13].

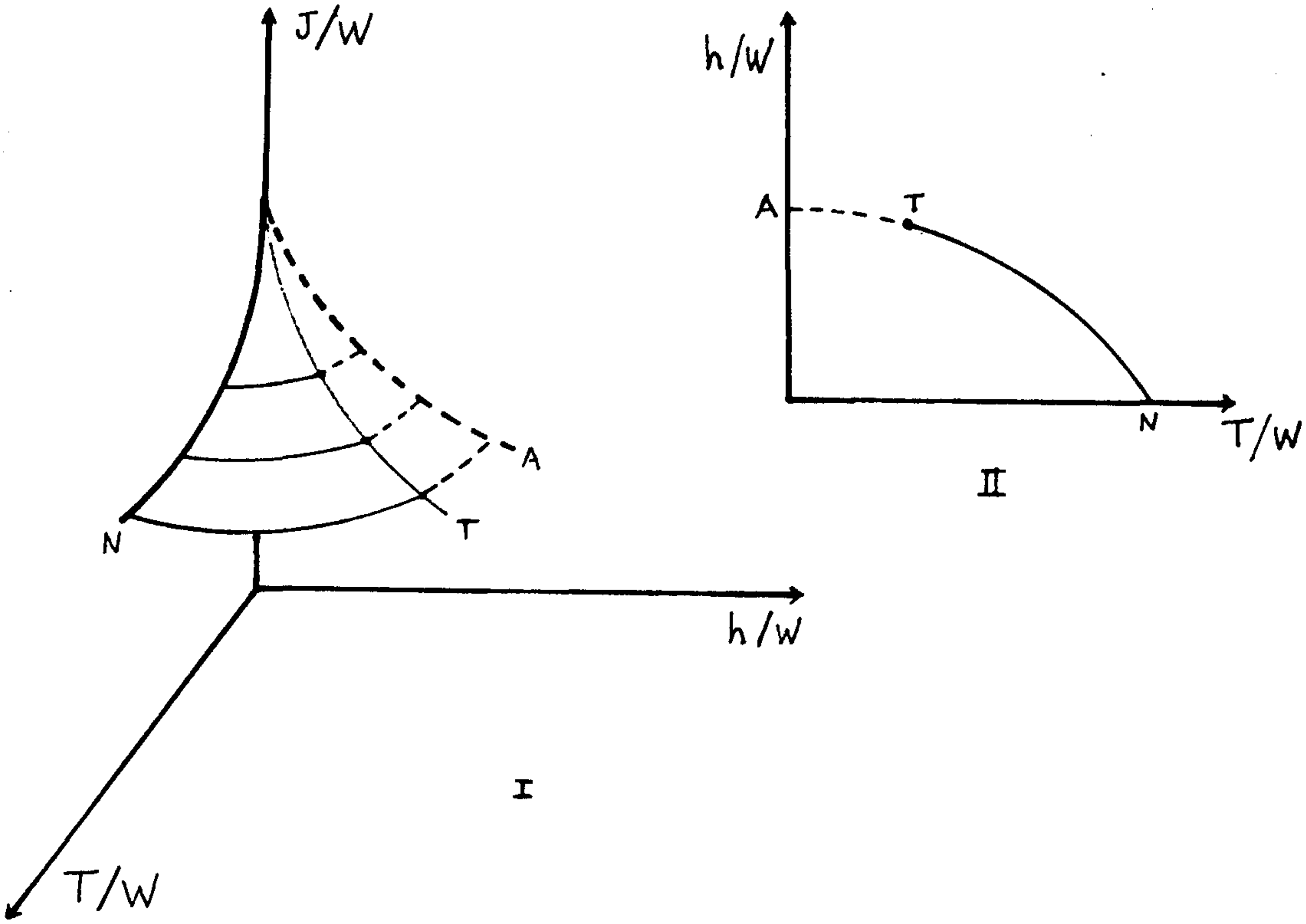

Fig. 3. — I) Generalized phase diagram (schematic) of the Kondo lattice for finite uniform magnetic field h. N represents the Neel line shown in figure 1 and (T) a line of tricritical points. II) Phase diagram of a metamagnet in the uniform field *versus* temperature plane. The continuous line represents second order transitions and the traced line is a line of first order transitions. T is a tricritical point.

The second main point is that for this $T = 0$ tricritical point the effective dimensionality, $d_{\text{eff}} = d + z$, is certainly larger than the upper critical dimension $d_c = 3$. This implies that the exponents associated with the zero temperature fixed point take classical values [3, 13]. In fact if we use the classical tricritical exponents $\alpha = 1/2$, $\nu = 1/2$ and assume $\phi_h = \nu z = 3/2$, with a tricritical exponent $\phi_t = \nu z/\phi_h = 1$, we can account for the pressure dependence of all the quantities shown in figure 2 in a consistent way. We get $\chi_0(T) \propto |j|^{-3/2} f_0(T/T_c)$, $\chi_h(T, h) \propto |j|^{-3/2} f_h(T/T_c,\ h/h_c)$ and $T_c \propto h_c \propto |j|^{3/2}$. Also these values for the exponents are compatible with the scaling form for the free energy $F \propto h_c(P) f\,[T/T_c(P),\ h/h_c(P)]$ with $T_c(P) \propto h_c(P)$ which was obtained previously on experimental ground by [14] Puech *et al.* and [8] Mignot *et al.*.

Although this expression has been used even in a predictive way [15], the analysis presented here put these results in a more general framework namely, the theory of quantum critical phenomena.

Notice that the value $\phi_h = \nu z = 3/2$ implies that the exponent σ which renormalizes the uniform magnetic field is $\sigma = 0$ so that h acts as a parameter whose renormalization is controlled by that of the coupling J at the $T = 0$ fixed point. The same applies for the temperature[3].

The value $z = 3$ for the dynamic critical exponent indicates ferromagnetic correlations [3, 16]. This is not surprising if we recall the phase diagram shown in figure 3 and the relevance of these ferromagnetic fluctuations at a $T = 0$ metamagnetic transition which for $(J/W) = (J/W)_c$ occurs at arbitrarily low fields. Notice that the exponents above violate the modified hyperscaling relation as expected [13] since $d + z > d_c = 3$ for a tricritical point.

A direct consequence of the above values for the critical exponents is that the ratio $A(P)/m_T^2(P) = [T_c(P)]^{-2}/m_T^2(P)$ (the equality being valid for a Fermi liquid) will turn out to be a constant independent of pressure. In fact since $2 - \alpha - 2\nu z = -3/2$ we find $m_T \propto T_c^{-1}$ and the result stated above. The constancy of the ratio $T_c^{-1}(P)/m_T(P)$ has been observed [17] in $CeCu_6$, UBe_{13} and UPt_3 but has not been verified yet in $CeRu_2Si_2$ due to the lack of specific heat measurements under pressure in this system.

From the scaling form for the uniform magnetization M at low temperatures $(T \ll T_c)$, $M \propto |j|^{2-\alpha-\phi_h} f(h/h_c)$ and the values $\alpha = 1/2$ and $\phi_h = 3/2$, we deduce $M \propto f(h/h_c)$. This implies that the metamagnetic-like transition in $CeRu_2Si_2$ at h_c will occur, for different pressures, always at the same fixed magnetization. This has indeed been observed on pressure studies in this system [8] and led to the above scaling expression for the magnetization [8, 14]. This scaling form for M, provides support for the values of the exponents given above. Another consequence of these values is that the "Wilson ratio" χ_0/m_T is independent of pressure.

An unambiguous confirmation of the above values for the exponents would come from measurements of the pressure dependence of the correlation length ξ obtained by neutron scattering [18]. We expect the ratio $[\xi(P = 0, T = 0)/\xi(P, T = 0)]^z$ with $z = 3$ to yield points on the line defined by the data in figure 2. It should be more convenient to work with a doped system (see below), closer to the magnetic instability and consequently with a larger correlation length, in order to get better accuracy. Also, we point out that dynamic experiments can give access to the critical relaxation time τ given by equation (1d). Nuclear magnetic resonance probes the Ce spin fluctuations [19] and these experiments carried under applied pressure can provide information on the exponents. Besides EPR measurements under pressure on dissolved magnetic impurities, like those performed by Schlott and Elschner [20] on $CeAl_3$, may yield equivalent information. The scaling of the nuclear relaxation rate T_1^{-1} has been obtained by Bourbonnais *et al.* [21] and the contribution due to antiferromagnetic spin fluctuations is found to be: $T_1^{-1} \propto \xi^{\gamma/\nu-d+z} \propto T_c^{-(\gamma/\nu-d+z)/z}$. In these equations γ, ν and z are the susceptibility (staggered), correlation length and dynamic exponents respectively. d is the dimensionality of the system. Since $\gamma = 1$, $\nu = 1/2$ for a classical tricritical point and $d = z = 3$ as obtained in the previous analysis, we get $T_1^{-1} \propto T_c^{-2/3}$ from which we can obtain its relative pressure dependence.

The scaling theory allows to make predictions concerning the pressure dependence of the Neel temperature T_N and critical field h_N for doped systems (see below) with J/W close to but smaller than $(J/W)_c$ i.e. in the antiferromagnetic region of the phase diagram shown in figure 1. In this case the ratios $T_N(P = 0)/T_N(P)$ and $h_N(P = 0)/h_N(P)$ should fall on the line defined by the data in figure 2. This is a consequence of generalized scaling [6], independent of the particular exponents, which predicts that, for example, the temperature exponent of the critical Neel line is the same than the coherence line i.e. $1/\nu z$.

Doping $CeRu_2Si_2$ with lanthanum [22] is equivalent to applying negative pressure in this system. At a critical concentration x_c of La of approximately [12] $x_c = 7\%$, $Ce_{1-x}La_xRu_2Si_2$ becomes antiferromagnetic at $T = 0$. The dependence of the Neel temperatures on x for $x > x_c$ has been determined for different concentrations [12]. The system at the critical concentration x_c, i.e., with $J/W = (J/W)_c$, is particularly interesting. From the phase diagram in figure 1 we notice that this system does not cross the coherence line and consequently does not enter the Fermi liquid regime. In fact taking into account a regular temperature dependent term in $|j|$, i.e., defining $j(T) = J/W - (J/W)_c + aT$ we find $c \propto T^{1/3}$ for $J/W = (J/W)_c$ and $T \Rightarrow 0$. This is clearly a non-Fermi liquid behavior although we may want to extend this concept and think in terms of a diverging thermal mass $m_T \propto C/T \propto T^{-2/3}$ at x_c. For the uniform susceptibility in very low fields we get $\chi_h \propto 1/T$ and for $T \ll T_c$, $\chi_h \propto 1/h$ at the critical composition.

We have presented a scaling analysis of the non-magnetic heavy fermion system CeRu$_2$Si$_2$ under applied pressure. As in a previous [23], although different, scaling approach we have attempted to explicitly determine the critical exponents associated with the zero temperature fixed point and which give rise to the scaling laws which were discovered experimentally. Based on considerations on the nature of the zero temperature transition and on the role of the uniform magnetic field we arrived at a particular set of exponents ($\alpha = 1/2$, $\nu = 1/2$, $\phi_t = \nu z/\phi_h = 1$, $z = 3$) which consistently describes all the data. They allow to make non-trivial predictions, which can be tested, like for example the relative pressure dependence of the correlation length and of the nuclear relaxation rate. It would be interesting to extend this analysis to other systems like Ce$_{1-x}$Si$_x$, which is close to a ferromagnetic instability and to those exhibiting superconducting behavior to look for the existence of different universality classes in heavy fermion systems.

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