

A METAMAGNETIC QUANTUM CRITICAL ENDPOINT IN $\text{Sr}_3\text{Ru}_2\text{O}_7$

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In this paper, we discuss the concept of a metamagnetic quantum critical end–point, consequence of the depression to zero temperature of a critical end–point terminating a line of first order first transitions. This new type of quantum critical point (QCP) is interesting both from a fundamental point of view: a study of a symmetry conserving QCP, and because it opens the possibility of the use of symmetry breaking tuning parameters, notably the magnetic field. In addition, we discuss the experimental evidence for the existence of such a QCP in the bilayer ruthenate $\text{Sr}_3\text{Ru}_2\text{O}_7$.

1 Introduction

The concept of a quantum critical point has grown to be an extensively investigated issue both theoretically [1–4] and experimentally [5–8]. The attractions of the problem are many–fold. From the fundamental point of view it allows the extension to the quantum regime of the challenges and paradigms generated by the study of critical phenomena. There is also the hope that it could offer a unified phenomenological framework for the understanding of a wide range of correlated electron behaviour. This would have technological implications, because the properties of many materials of practical interest would then be governed by their proximity to a QCP.

Recently, we have worked on a novel form of quantum criticality, identifying what we believe to be a quantum critical end–point associated with metamagnetism in $\text{Sr}_3\text{Ru}_2\text{O}_7$. In this paper we will give a qualitative discussion of the general features of quantum criticality in itinerant ferromagnets, in order to emphasise the similarities and differences between ‘traditional’ quantum critical points, which are associated with spontaneous symmetry breaking, and the quantum critical end–point, which is not.

Usually, a quantum critical point is created by the depression of a second order phase transition to zero temperature by means of a non–thermal external parameter p , as illustrated in Fig. 1. For $p = 0$, the transition at T_c is thermal, with the symmetry of the high temperature disordered phase spontaneously broken. Around the transition point, there is the well–known critical region associated with such a classical phase transition. If T_c is lowered by the application of the non–thermal parameter p , the width of the classical critical region shrinks, until it disappears altogether at $T_c = 0$. In this case criticality is purely of the quantum type, in which (since momentum and coordinates operators do not commute) the temporal and spatial components cannot be decoupled. There is a third region of criticality, that marked “quantum critical” in Fig. 1, in which fluctuations

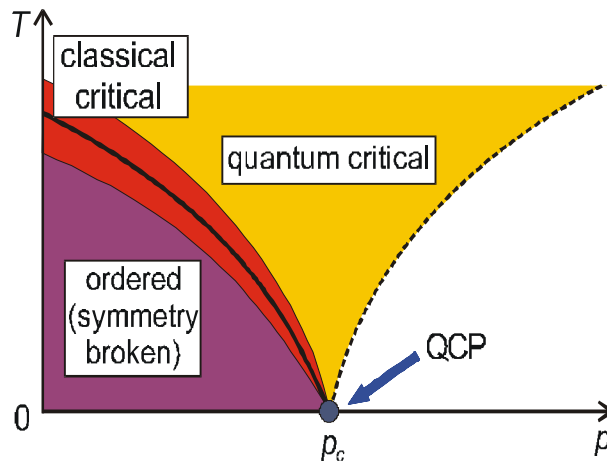


Figure 1. Schematic phase diagram of a second order phase transition giving rise to a quantum critical point at p_c .

controlled by the quantum critical point are thermally excited, which explains the decrease in its width as the temperature falls. The other significant point of note is the extent of the quantum critical region up the temperature axis; fluctuations associated with quantum critical points are thought to play an important role in determining the properties of correlated electron systems even at room temperature and above. The treatment of a QCP differs from the classical one not by the introduction of new ingredients *ad hoc*, but rather from the fact that simplifications normally made when considering the latter are no longer valid.

A physically appealing way to understand the interplay between the temporal and spatial domains is provided by the relation $\Delta E \Delta t \geq \hbar$. If the characteristic thermal time $\tau_{\text{thermal}} = \hbar/k_B T$ is much less than τ , the characteristic time of the spatial fluctuations, the system appears static. This then justifies a classical treatment in the vicinity of T_c , because τ diverges during critical slowing down. Further away from T_c , however, this is not the case, and a proper quantum mechanical treatment is required. As T_c drops to zero, τ_{thermal} itself diverges, and the system never enters the classical regime.

In treating the quantum regime, it is customary to do something like the reverse of the above: treat the temporal variation of the fluctuations as extra effective spatial dimensions (in imaginary time), and so map the quantum system to a classical one of higher dimension. In general, imaginary time plays the role of z (coupled) spatial dimensions, where z is the dynamic exponent, whose value is related to the universality class of the transition. The role of the temporal dimensions can then be understood in a finite size analysis, because the system size in any temporal direction (L_t) is determined by the inverse temperature. If $T_c = 0$, the system is infinite in all directions, and a treatment in $d+z$ dimensions is appropriate. At any finite temperature the importance of the temporal fluctuations is cut off by the finite L_t as their correlation length attempts to diverge. Closer to the transition than this, only the genuine spatial correlation lengths are diverging, signalling the crossover from the quantum $d+z$ -dimensional treatment to a regime in which a classical d -dimensional treatment is adequate. Since L_t is inversely proportional to temperature, this 'saturation' of the temporal fluctuations happens further from the phase transition line as the temperature increases.

As stressed in the above discussion, the key step in producing the full quantum critical region' from fig. 1 is to produce a phase change with associated diverging susceptibilities at $T = 0$. A standard first order phase transition would not be appropriate in this context, because it does not give a source of diverging

susceptibilities. At first sight, this seems to lead to the conclusion that quantum criticality must be associated with only second order phase transitions, and hence with symmetry–broken phases.

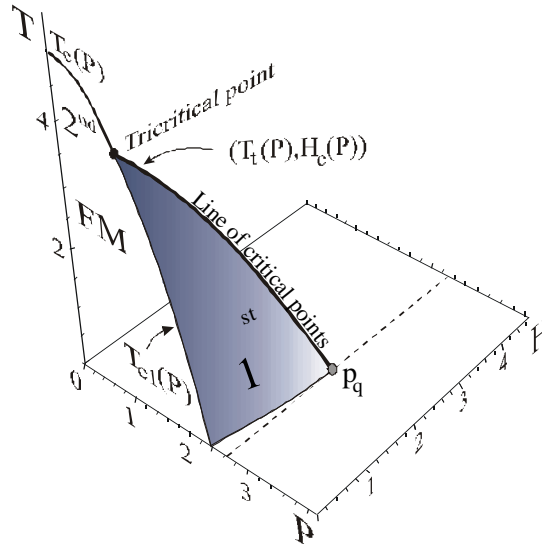


Figure 2. Schematic (P,H,T) phase diagram of an itinerant ferromagnet.

In this context, a series of recent observations giving hints for quantum critical behaviour associated with metamagnetism [9–13] were something of a surprise. Metamagnetism is empirically defined as a sudden non–linear rise in magnetisation at some finite applied field. It cannot be a second order phase transition, because the low and high field states are of the same symmetry. It must either be a first order phase transition, with the consequent discontinuous jump in the magnetisation, or simply a crossover. The former case is in close analogy to the liquid to gas transition in water, the difference in the value of the magnetisation between the two states playing the role analogous to the difference in density of vapour and liquid water. At first sight, neither of these can be a source of the required diverging susceptibilities. However, due to the symmetry conservation between the two phases, it is possible for this first order line to end at a critical end–point (CEP), again in close analogy to the situation in water. The CEP shares the property of a second order phase transition that is the key to producing quantum criticality, since it is characterised by diverging susceptibilities and the physics is dominated by fluctuations. The main qualitative difference is the absence of any spontaneous breaking of symmetry. The possibility of a new type of quantum critical point is now apparent: that which would arise from the depression of the critical end–point temperature to zero by means of some tuning parameter. As we now discuss, this can occur in itinerant ferromagnets.

An itinerant ferromagnet has a rich P,H,T phase diagram (see fig 2): at $H=0$ the ferromagnetic to paramagnetic phase transition is second order below a certain pressure p^* , and first order for higher pressures[14]. Any non–zero magnetic field induces a finite magnetisation in the system; the symmetry associated with the ferromagnetic transition is broken and the second order phase transition can no longer take place. On the other hand, since there are no symmetry constraints on the first order transition, it extrudes into a surface in (P,H,T) of first order phase transitions that separate states with quantitatively different degrees of magnetisation (the metamagnetic transition). The tricritical point at p^* extrudes in

turn into a line of critical end points that bounds the surface of first order transitions. At a particular point (p_q, H_q) of the pressure and magnetic field, the line reaches $T=0$, giving rise to a quantum critical end–point (QCEP). Keeping the pressure fixed at p_q it is possible then to use the magnetic field to tune in and out of criticality.

This reasoning is appealing, but clearly in need of experimental investigation. In principle, these would be difficult experiments, requiring simultaneous application of high pressures and magnetic fields. However, it should be noted that both the *origin* and scale of the P axis depends on the particular compound which is being considered, if we appeal to the standard analogy between interatomic bonding and effective chemical pressure. In what follows we will argue that the magnetic behaviour of the ruthenate $\text{Sr}_3\text{Ru}_2\text{O}_7$ can be described within the framework that we have discussed above, and furthermore, that p_q for this system sits very close to ambient pressure. This last point is an issue of considerable experimental importance: in isolation, the applied magnetic field is an extremely easy parameter to control.

2 The system $\text{Sr}_3\text{Ru}_2\text{O}_7$

The basic physical properties of $\text{Sr}_3\text{Ru}_2\text{O}_7$ have been described in various reports [15–17]. The main development of significance was the discovery by Ikeda, Maeno and co–workers of techniques for the image–furnace growth of high purity single crystals. This work was extended by Perry to produce crystals with residual resistivity $\rho_{\text{res}} \sim 2 \mu\Omega\text{cm}$. In weak applied fields these crystals are strongly enhanced paramagnets down to the lowest temperatures, and metamagnetism is seen with transition fields of approximately 7.8 tesla for $H // c$ and 5.5 tesla for $H // ab$. Preliminary work on the properties in the vicinity of metamagnetism gave evidence for critical fluctuations, notably the behaviour of the resistivity exponent as a function of field and temperature, and the observation of an apparent logarithmic divergence of C/T vs. T in a field of approximately 7.8 tesla applied parallel to c [16]. This work was far from conclusive, however. Only one decade of temperature was investigated, and the results gave hints rather than proof of the existence of a QCEP. As can be seen from examination of Fig. 1, high temperature ‘quantum critical’ signatures can be observed if experiments are performed some distance in phase space away from a critical point, particularly at elevated temperatures.

To investigate the system in more detail, a transport study with $H // c$ was performed at lower temperatures (Grigera *et al.* [17]). To separate the different contributions to the resistivity the data were analysed using the expression $\rho = \rho_{\text{res}} + AT^\alpha$. ρ_{res} is the resistivity due to elastic scattering, the exponent α provides information about the temperature dependence of the resistivity, and A is a temperature independent coefficient related to the square of the quasi–particle effective mass. Both the temperature dependence and the residual part of the resistivity show pronounced changes when the field is swept through the metamagnetic transition, but the most significant finding concerns the behaviour of A . As seen in Fig. 3, A diverges as the metamagnetic transition is approached. The experiments and the way in which A was extracted (both described in detail in ref [17]) mean that it is effectively a probe for diverging susceptibilities along the $T=0$ axis. The fact that these were observed gives very good evidence that a QCEP of the class described above exists at ambient pressure in $\text{Sr}_3\text{Ru}_2\text{O}_7$.

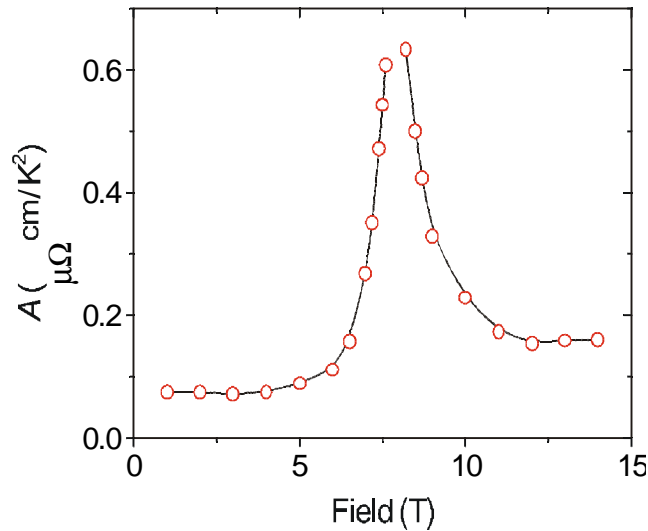


Figure 3. Divergence of the A coefficient as a function of the magnetic field in the neighbourhood of the metamagnetic field $H_c=7.785$ tesla (data from Ref. [17]).

3 Conclusions and future directions

We have discussed a new form of quantum criticality in itinerant fermionic systems based on a *quantum critical end-point* (QCEP) in which no symmetry is broken at the transition. This will hopefully open the way to new avenues of investigation. Firstly, it shows that discovery of a spontaneously-symmetry-broken phase is not a necessary step in establishing the existence of a quantum critical point. It also removes a significant restriction on tuning parameters for traditional QCP's, namely that the tuning parameter cannot break the same symmetry as the ordered phase in Fig. 1. Finally, there is the possibility of observing even more anomalous behaviour right in the vicinity of the QCEP. Novel ordered phases have been seen in this region near traditional QCP's (*e.g.* [7]), and may also exist near QCEP's. In the latter case, the ability to use symmetry-breaking tuning parameters may promote genuinely new behaviour. Intriguing preliminary evidence for this has already been seen in $\text{Sr}_3\text{Ru}_2\text{O}_7$ [17], and is worthy of detailed further investigation. Metamagnetism in itinerant ferromagnets is likely to be an ideal testing ground for these ideas. Magnetic field is a convenient tuning parameter, hopefully allowing the construction of a unified picture of the consequences of quantum criticality in clean itinerant systems.

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References

1. J. A. Hertz, Quantum critical phenomena *Phys. Rev. B* **14** (1976), pp. 1165–1184.
2. A. J. Millis, Effects of a nonzero temperature on quantum critical points in itinerant fermion systems, *Phys. Rev. B* **48** (1993), pp. 7183–7196.
3. S. Sachdev, Quantum phase transitions (Cambridge University Press, Cambridge 1999).
4. S. L. Sondhi, S. M. Girvin, J. P. Carini and D. Shahar, Continuous quantum phase transitions, *Rev. Mod. Phys.* **69** (1997) pp. 315–333.
5. C. Pfleiderer, G. J. McMullan, S. R. Julian, and G. G. Lonzarich, Magnetic quantum phase transition in MnSi under hydrostatic pressure *Phys. Rev. B* **55** (1997), pp. 8330–8338.
6. H. v. Löhneysen, T. Pietrus, G. Portisch, H. G. Schlager, A. Schröder, M. Sieck, and T. Trappmann, Non-Fermi-liquid behavior in a heavy-fermion alloy at a magnetic instability, *Phys. Rev. Lett.* **72** (1994), pp. 3262–3265.
7. N. D. Mathur, F. M. Grosche, S. R. Julian, I. R. Walker, D. M. Freye, R. K. W. Haselwimmer and G. G. Lonzarich, Magnetically mediated superconductivity in heavy fermion compounds, *Nature* **394** (1998), pp. 39–43.
8. D. Bitko, T. F. Rosenbaum and G. Aeppli, Quantum Critical Behavior for a Model Magnet, *Phys. Rev. Lett.* **77** (1996), pp. 940–943.
9. J. S. Kim, D. Hall, K. Heuser and G. R. Stewart, Indications of non-Fermi liquid behaviour at the metamagnetic transition of Upt_3 , *Solid State Comm.* **114** (2000), pp. 413–418.
10. H. Sugawara, Y. Aoki, H. Sato, N. Mushnikov and T. Goto, New heavy Fermion metamagnet, *J. Phys. Soc. Jpn.* **68** (1999), pp. 1094–1097.
11. S. Kambe, H. Suderow, J. Flouquet, P. Haen and P. Lejay, Field-induced renormalization observed by magnetoresistance in CeRu_2Si_2 , *Solid State Comm.* **95** (1995), pp. 449–443 ; **96** (1995), pp. 175–177.
12. Y. Aoki, T. D. Matsuda, H. Sugawara, H. Sato, H. Ohkuni, R. Settai, Y. Onuki, E. Yamamoto, Y. Haga, A. V. Andreev, V. Sechovsky, L. Havela, H. Ikeda, and K. Miyake, Thermal properties of metamagnetic transition in heavy-fermion systems, *J. Magn. Magn. Mater.* **177** (1998), pp. 271–276.
13. S. R. Julian, F. V. Carter, F. M. Grosche, R. K. W. Haselwimmer, S. J. Lister, N. D. Mathur, G. J. McMullan, C. Pfleiderer, S. S. Saxena, I. R. Walker, N. J. W. Wilson, G. G. Lonzarich, Non-Fermi-liquid behaviour in magnetic d- and f-electron systems, *J. Magn. Magn. Mater.* **177** (1998), pp. 265–270.
14. It has been argued that non analytic terms would drive all ferromagnetic transitions first order, see D. Belitz, T. R. Kirkpatrick and T. Vojta, First order transitions and multicritical points in weak itinerant ferromagnets, *Phys. Rev. Lett.* **82** (1999), pp. 4707–4710.
15. S. Ikeda, Y. Maeno, S. Nakatsuji, M. Kosaka and Y. Uwamoto, Ground state in $\text{Sr}_3\text{Ru}_2\text{O}_7$: Fermi liquid close to a ferromagnetic instability, *Phys. Rev. B* **62** (2000), pp. R6089–R6092.
16. R. S. Perry, L. M. Galvin, S. A. Grigera, L. Capogna, A. J. Schofield, A. P. Mackenzie, M. Chiao, S. R. Julian, S. Ikeda, S. Nakatsuji, Y. Maeno and C. Pfleiderer, Metamagnetism and critical fluctuations in high quality single crystals of the bilayer ruthenate $\text{Sr}_3\text{Ru}_2\text{O}_7$, *Phys. Rev. Lett.* **86** (2001), pp. 2661–2664.
17. S. A. Grigera, R. S. Perry, A. J. Schofield, M. Chiao, S. R. Julian, G. G. Lonzarich, S. I. Ikeda, Y. Maeno, A. J. Millis and A. P. Mackenzie, Magnetic field-tuned quantum criticality in the metallic ruthenate $\text{Sr}_3\text{Ru}_2\text{O}_7$, *Science* **294** (2001) pp.329–322.