Low temperature thermal and electrical transport properties of ZrZn$_2$ in high magnetic field

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Abstract. The low temperature electrical and thermal transport properties of the itinerant ferromagnet ZrZn$_2$ were investigated in order to explore the nature of the Fermi-liquid breakdown in this material. We have implemented electrical and thermal conductivity measurements down to temperatures of 100 mK and in high magnetic field. In zero field and above 2 K the electrical and effective thermal resistivities take a $T^{5/3}$ and $T$-linear form, respectively. These are the signatures of the marginal Fermi-liquid, predicted to occur close to a ferromagnetic quantum critical point by spin fluctuation theory. In contrast, we find that below 2 K and in external magnetic field the electrical resistivity assumes a quadratic temperature dependence, consistent with a return to conventional Fermi-liquid behaviour.

1. Introduction
Metals close to a ferromagnetic quantum critical point offer a comparatively clear and well-defined environment to investigate the breakdown of Landau’s Fermi liquid theory. Since the interaction between quasiparticles is strongly enhanced by magnetic fluctuations, Fermi liquid theory can break down, leading to unconventional low temperature properties. The investigated material, ZrZn$_2$, undergoes the weakest form of a Fermi liquid breakdown, for which the quasiparticle scattering rate $\tau^{-1}$ is proportional to the excitation energy $\epsilon$. This is the signature of the marginal Fermi liquid state, which separates the conventional Fermi liquid ($\tau \propto \epsilon^2$) from more exotic forms of Fermi liquid breakdown.

Standard theory based on low-frequency, long-wavelength spin fluctuations predicts the appearance of the marginal Fermi liquid state in a three dimensional system close to a ferromagnetic quantum critical point [1, 2, 3, 4]. The underlying quasiparticle scattering rate leads to characteristic temperature dependences for key transport properties, such as a $T^{5/3}$ form for the electrical resistivity and a $T$-linear form for the effective thermal resistivity $\omega$.

2. Experimental details
The transition metal compound ZrZn$_2$ crystallizes in the cubic Laves structure C15. As a d-band itinerant ferromagnet it orders magnetically below $T_c = 28.5$ K with a small ordered moment of $\mu \approx 0.17 \mu_B$/f.u. in the limit $T \to 0$ and $B \to 0$ [5]. In contrast, the Curie-Weiss moment in the paramagnetic regime ($\mu_{\text{eff}} = 1.9 \mu_B$/f.u.) is well above the ordered moment [1]. Furthermore,
ferromagnetism can be suppressed by a hydrostatic pressure of 20 kbar, which suggests that the system lies in the vicinity of a ferromagnetic quantum critical point [6, 7]. Inelastic neutron scattering shows highly dispersive spin density relaxation rates which supports the applicability of spin fluctuation theory [8].

We measured three single crystal samples with different residual resistivities of \(\rho_0 = 6.88 \, \mu\Omega \text{cm} \) (RRR=11), \(\rho_0 = 1.34 \, \mu\Omega \text{cm} \) (RRR=48) and \(\rho_0 = 0.96 \, \mu\Omega \text{cm} \) (RRR=68). They were cut into a typical geometry of \(2 \, \text{mm} \times 0.5 \, \text{mm} \times 0.2 \, \text{mm} \) and contacted in a four wire geometry with a micro-spot-welding technique to give low contact resistance.

Resistivity measurements were carried out using a four terminal ac technique in a \(^4\text{He} \) cryostat (PPMS) and an adiabatic demagnetisation refrigerator down to 100 mK. The measurements were repeated with several different excitation currents between 0.3 mA and 1 mA to ensure reliability.

Thermal conductivity was measured with a one-heater, two-thermometer method in a PPMS and a dilution refrigerator down to 100 mK. The setup was tested by comparing the electrical and thermal transport data in silver wire, obtaining the Wiedemann-Franz law. A temperature gradient of typically 3% – 5% was applied for the thermal conductivity measurement.

### 3. Experimental results

Figure 1 shows the resistivity of three ZrZn\(_2\) samples with different impurity levels. A non-Fermi-liquid behaviour of the form \(\rho = \rho_0 + a T^{5/3}\) is clearly visible from 2 K to approximately

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**Table 1:** Temperature dependence of the transport properties

| Transport Property | Fermi Liquid | Marginal Fermi Liquid |
|--------------------|--------------|-----------------------|
| Electrical Resistivity \(\rho\) | \(\rho = \rho_0 + AT^2\) | \(\rho = \rho_0 + a T^{5/3}\) |
| Thermal Resistivity \(w = L_0 T/\kappa\) | \(w = w_0 + AT^2 + BT^2\) | \(w = w_0 + a T^{5/3} + b T\) |
| \(\delta = w - \rho\) | \(\delta = BT^2\) | \(\delta = b T\) |

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**Figure 1:** Main: Electrical resistivity of three different ZrZn\(_2\) samples. Inset: Resistivity plotted versus \(T^{5/3}\). The straight lines are guides to the eye.

**Figure 2:** Thermal conductivity of two different ZrZn\(_2\) samples.
16 K, in agreement with recent investigations \[9, 10\]. This indicates that the dominant scattering is caused by spin fluctuations in this temperature range. We can rule out phonon scattering as the origin of this unusual power law, since it would lead to a higher power in the temperature dependence of the resistivity. Above 16 K, however, the measured resistivity exceeds the $T^{5/3}$ temperature dependence, suggesting that phonon scattering becomes increasingly relevant.

In a system like ZrZn$_2$ the thermal conductivity at low temperature consists of contributions from electrons, phonons and magnons ($\kappa_{\text{tot}} = \kappa_{\text{el}} + \kappa_{\text{ph}} + \kappa_{\text{mag}}$). The magnon contribution is negligible due to the very small ordered moment in ZrZn$_2$. The phonon contribution can be isolated by comparing samples with different impurity levels, since $\kappa_{\text{ph}}$ is not significantly affected by the presence of impurities. Figure 2 shows the thermal conductivity of two different samples. A characteristic peak appears at 15 K for the purer sample, but is strongly suppressed by impurity scattering in the second sample. The large difference in magnitude shows that the system is highly sensitive to elastic scattering from impurities. Additionally, we can conclude that the electronic contribution must dominate in this temperature range, which agrees with a detailed analysis of the phonon contribution. After isolating and subtracting the phononic part, we define the effective thermal resistivity $w$ using the Wiedemann Franz law:

$$w = \frac{L_0 T}{\kappa_{\text{el}}},$$

with the Lorentz number $L_0$. When comparing heat and charge transport, there is a crucial difference in the underlying scattering mechanics. While the electrical current is only reduced by large angle quasiparticle scattering, the heat current is also affected by inelastic small angle scattering. Thus, the difference between the thermal resistivity $w$ and the electrical resistivity $\rho$, defined as

$$\delta = w - \rho,$$

reveals information about the latter process.

Figure 3 illustrates the linear temperature dependence in $\delta$, which also indicates the dominant inelastic scattering from spin fluctuations. In contrast, phonon scattering would give rise to a $T^3$ term the effective thermal conductivity $w$. Both the electrical and the thermal transport

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**Figure 3:** The difference $\delta = w - \rho$ of the thermal ($w$) and electrical resistivities ($\rho$) versus temperature for the sample with $\rho_0 = 6.88 \, \mu\Omega \text{cm}$. The straight line is a power fit of the form $\delta = bT^c$ yielding the exponent $c = 1.03$.

**Figure 4:** Electrical resistivity for the sample with $\rho_0 = 1.34 \, \mu\Omega \text{cm}$ in different magnetic fields.
measurements clearly show an unusual non Fermi-liquid behaviour in ZrZn$_2$ at low temperature. However, the data also illustrate why measurements on a sample with about an order of magnitude lower impurity level were required to achieve the high quality of thermal conductivity data evident in [6].

Figure 4 shows the temperature dependence of the resistivity in ZrZn$_2$ at different magnetic fields. At low temperature the resistivity increases with increasing field. Such a positive magnetoresistance at low T is frequently observed in clean metals. With increasing temperature, however, scattering from spin fluctuations becomes more significant in limiting the charge transport. The application of an external magnetic field suppresses the fluctuations which in turn leads to the negative magnetoresistance at high temperature.

For a detailed treatment of the resistivity exponent in magnetic field, resistivity data down to 100 mK are plotted in Figure 5. At high temperature above 10 K the resistivity in all fields assumes $T^{5/3}$ dependence in agreement with Figure 1. At low temperature, however, the resistivity recovers a $T^2$ dependence, characteristic for a Fermi liquid. The crossover temperature, at which the resistivity exponent changes from 2 to 5/3 is strongly field dependent. In zero field the $T^2$ dependence recovers below 2 K, whereas at 9 K the Fermi liquid behaviour is evident from the lowest temperature up to 7 K. The recovery of $T^2$ law and its strong field dependence can be explained by the suppression of spin fluctuations in magnetic field, as suggested by measurements of the electronic specific heat [11]. It also shows that ZrZn$_2$ is indeed a Fermi liquid in the low temperature limit, and suggests that disorder scattering is not responsible for the $T^{5/3}$ form observed at high temperature.

The above presented temperature dependences in the transport data agree with the theoretical predictions of spin fluctuation theory and suggest that ZrZn$_2$ can be described as a marginal Fermi liquid over a wide range of temperature, field and pressure.

![Figure 5: Electrical resistivity of ZrZn$_2$ in different magnetic fields. In the left diagram the resistivity is plotted versus $T^2$, in comparison the same data set is plotted vs. $T^{5/3}$ in the right diagram. The straight lines are fits to the data at high temperature (left) and low temperature (right), respectively.](image)

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