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Scaling between magnetic field and temperature in the high-temperature superconductor $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$

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Many exotic metallic systems have a resistivity that varies linearly with temperature, and the physics behind this is thought to be connected to high-temperature superconductivity in the cuprates and iron pnictides^{1–9}. Although this phenomenon has attracted considerable attention, it is unclear how the relevant physics manifests in other transport properties, for example their response to an applied magnetic field. We report measurements of the high-field magnetoresistance of the iron pnictide superconductor $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ and find that it obeys an unusual scaling relationship between applied magnetic field and temperature, with a conversion factor given simply by the ratio of the Bohr magneton and the Boltzmann constant. This suggests that magnetic fields probe the same physics that gives rise to the T -linear resistivity, providing a new experimental clue to this long-standing puzzle.

Within both the copper- and iron-based superconductor families, the chemical compositions that exhibit the highest transition temperatures show a distinct T -linear resistivity extending down to the superconducting critical temperature, T_c (refs 2–4). This phenomenon appears in many metals thought to have a quantum critical point (QCP), including the heavy fermion and ruthenate compounds^{10,11}, where the temperature dependence of the resistivity acquires a distinctive power-law form in the immediate vicinity of the QCP and, where it is linear, its slope may be universal¹⁷. Indeed the prevalence of the phenomenon has led to the proposal that it is the result of universal scaling behaviour familiar from classical phase transitions⁸. Although the mechanism behind T -linear resistivity in high-temperature superconductors is the subject of spirited debate, it has been suggested that quantum critical physics leads to both T -linear resistivity and high-temperature superconductivity in these systems^{5,6,12,13}. Evidence consistent with this idea continues to grow^{12,14–18}.

The universal behaviour that emerges near a classical second-order phase transition is well understood. At such a transition the system will have strong fluctuations on all length scales, and thus no intrinsic length scale. On approach to the transition, some thermodynamic quantities will exhibit power-law behaviour with a characteristic exponent. These exponents will often be common to a large number of systems that form a universality class. In this regime the dependence of measurable quantities on external parameters often has a scaling form where one or more parameters always enters normalized to some other parameter (for example magnetic field to temperature measured from the critical temperature, $H/(T - T_c)$).

These scaling forms are a direct consequence of the fact that the system does not itself have an intrinsic length scale, and so once one external parameter is fixed it sets the scale from which all others will be measured. Scaling behaviour is thus an important signature of critical physics. At a quantum critical point this idea extends naturally to dynamical quantities such as the resistivity, because these systems also have a diverging timescale. For example, it has been argued that the collapse of the optical conductivity as a single function of $\hbar\omega/k_B T$ in $\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{Y}_x\text{Cu}_2\text{O}_{8+\delta}$ is evidence of a QCP¹². In this work, we report the observation of a new kind of scaling behaviour in the transport properties of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$, a material thought to be near a QCP^{2,19–24}, where the resistance as a function of applied magnetic field H and temperature T scale together with the same exponent, suggesting that the resistance can be described as a single variable given by the quadrature sum of H and T .

The parent compound of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ is an antiferromagnetic (AFM) metal with a Néel temperature of 140 K. Concurrent with the appearance of magnetic order, the parent compound undergoes a structural transition from tetragonal to orthorhombic. With the substitution of phosphorous for arsenic, these two transitions are suppressed and a superconducting ground state emerges, resulting in the phase diagram shown in Fig. 1a. The AFM and structural transition extrapolate to $T = 0$ K near $x \approx 0.3$, beneath the superconducting dome. Near this substitution level, the resistivity has a linear temperature dependence over a broad temperature range^{2,24}. These materials were very quickly recognized to be a possible new arena for the exploration of quantum criticality¹⁹, and the T -linear resistivity, along with the quasiparticle mass enhancement observed in heat capacity and de Haas–van Alphen measurements^{22,23}, have lent support to this idea.

We have measured the in-plane transverse magnetotransport ($H \parallel c$, current $\perp c$) of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ up to $H = 92$ T, at several dopings, starting at $x = 0.31$ and extending to the edge of the superconducting dome on the overdoped side. Single crystals were grown by a self-flux method described elsewhere²⁵. The composition of these materials was previously determined using X-ray photoelectron spectroscopy. The samples used in this study were taken from the same or similar batches, and found to have the anticipated T_c , which correlates well with composition x . Resistance was measured by a standard four-probe AC lock-in method, and magnetic fields of up to 92 T were accessed at the NHMFL Pulsed Field Facility, Los Alamos National Laboratory. Contact resistances

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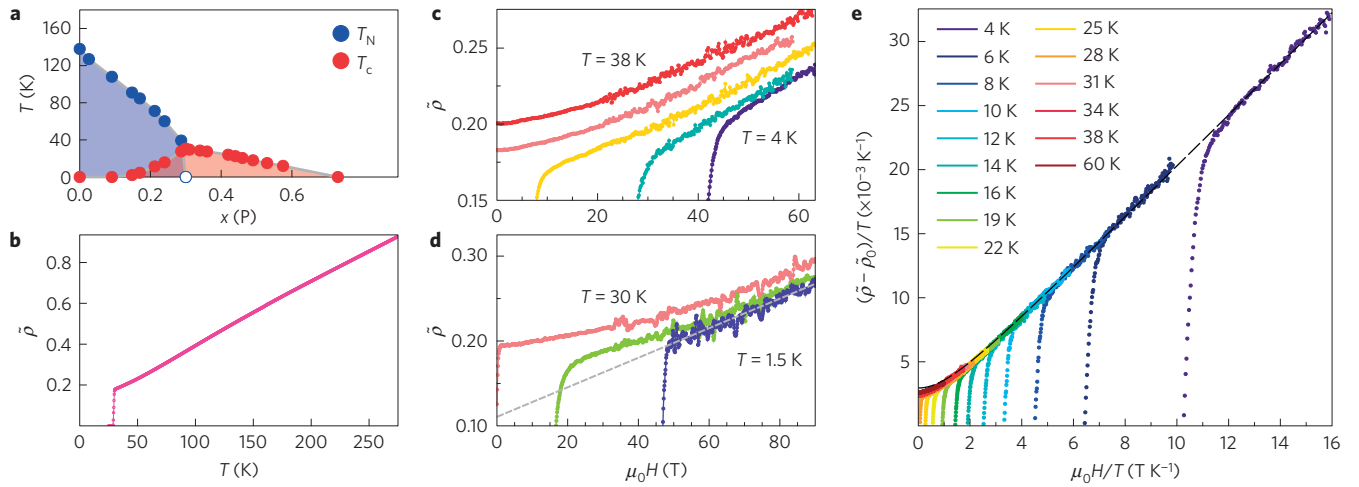


Figure 1 | $H - T$ scaling in $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ at $x = 0.31$. **a**, Phase diagram of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ showing the boundaries of the AFM-orthorhombic phase (blue) and superconducting (red) phases in $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$. The open circle marks the position of the putative quantum critical point². **b**, Temperature dependence of the resistivity for sample S1 with $x = 0.31$. **c**, Resistivity versus magnetic field for sample S1 at 4 K (lowest curve), 14 K, 25 K, 31 K and 38 K. **d**, MT of a second sample (S2) of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$, also at $x = 0.31$, extending up to 92 T, this time at temperatures 1.5 K, 20 K and 30 K. The linear MT extrapolates to the same $\tilde{\rho}_0$ as the temperature-dependent data shown in **b** (see Supplementary Information), indicated by the dashed line. **e**, Scaling plot of the MT curves from sample S1 (those in **c** and others). After subtracting the residual resistivity $\tilde{\rho}_0$, the remainder is divided by temperature and plotted against H/T . The data are approximated well by a function proportional to $\sqrt{1 + c(\mu_0 H/T)^2}$, where c is a numeric parameter (grey dashed line).

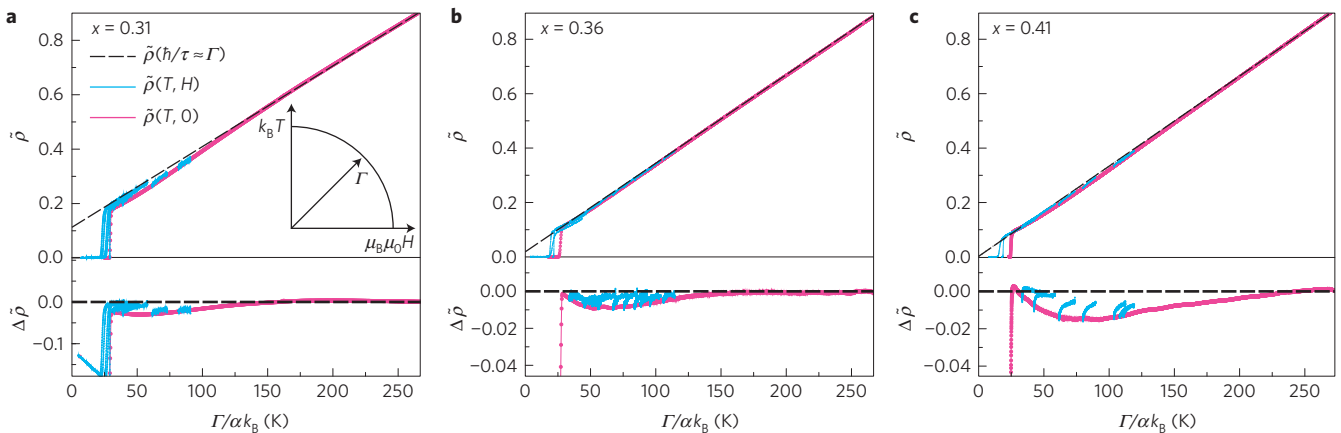


Figure 2 | Magnetotransport of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ as a function of Γ near optimal T_c . **a-c**, The MT (blue) plotted as a function Γ approaches the same linear dependence as the zero-field resistance (pink) for the three compositions shown: $x = 0.31$ (**a**), $x = 0.36$ (**b**) and $x = 0.41$ (**c**). Lower panels show the same data with the linear component, $\tilde{\rho} \propto \Gamma$ (black dashed line), subtracted, and with the lowest temperature curves removed for clarity. The inset of **a** shows a schematic representation of the relationship between T , H and Γ . The room temperature resistivities used to normalize these data were $351 \mu\Omega \text{ cm}$, $338 \mu\Omega \text{ cm}$, $270 \mu\Omega \text{ cm}$, respectively.

of around $\sim 1 \Omega$ were achieved by sputtering gold onto the samples and attaching gold wires with EpoTek H20E.

In Fig. 1b we show the resistance versus temperature for a sample (S1) of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ at $x = 0.31$ exhibiting the characteristic high-temperature T -linear behaviour. Because geometric factors do not influence any of our analysis, the data for each sample are normalized to the room temperature value $\tilde{\rho} = \rho/\rho(300)$. Figure 1c shows the magnetotransport (MT) data for the same sample, which exhibit an H -linear dependence at high fields. Indeed, this H -linear MT extends to the highest magnetic field available to us ($\mu_0 H = 92 \text{ T}$), without any sign of saturation, and is reproducible between samples (compare with sample S2 in Fig. 1d). In searching for scaling behaviour in the MT, we compare the T -linear and H -linear dependent components of the resistivity directly by subtracting the residual resistivity. Normalizing with respect to temperature and plotting versus H/T , we see in Fig. 1e that the data collapse onto a single curve. Note that this scaling is

distinct from the Köhler scaling²⁶ that should apply to conventional orbital MT and that is known to be strongly violated in these systems². The form of the H/T scaling motivates the following ansatz for the description of the (T, H) -dependent resistance:

$$\rho(H, T) - \rho(0, 0) \propto \sqrt{(\alpha k_B T)^2 + (\gamma \mu_B \mu_0 H)^2} \equiv \Gamma \quad (1)$$

where we have introduced a new energy scale Γ associated with the quadrature sum of temperature and applied field, appropriately scaled using the Boltzmann constant k_B , the Bohr magneton μ_B and the dimensionless parameters α and γ . The ratio γ/α can be determined directly from the ratio of the slopes of $\rho(T, 0)$ and $\rho(0, H)$ (the latter is simply taken at $T = 4 \text{ K}$). Because the resistivity curve in Fig. 1b develops some curvature at low temperatures, we take the slope from the T -linear, high-temperature region and find that $\gamma/\alpha = 1.01 \pm 0.07$ (see Supplementary Information for details). We find that $\rho(0, 0)$ is the same when linearly extrapolated from the

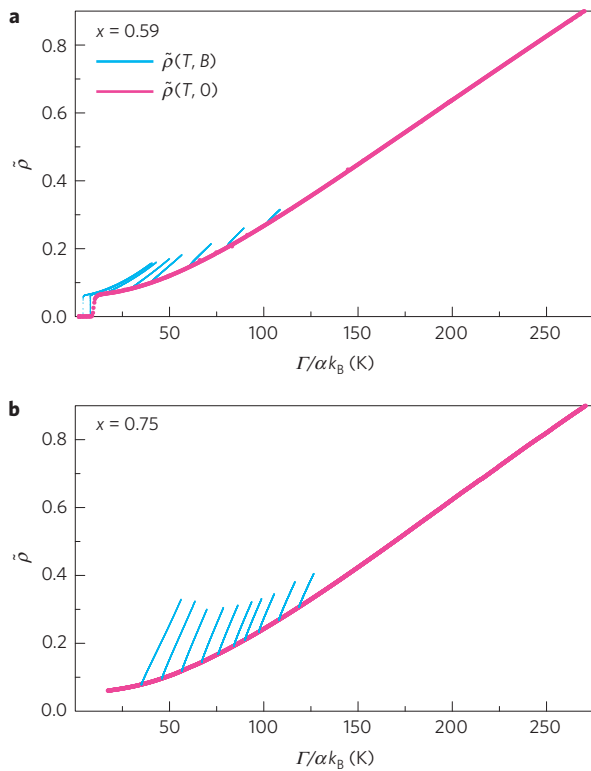


Figure 3 | Magnetotransport of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ at two values of x , far from optimal doping. **a, b**, A figure analogous to Fig. 2 showing the resistance as a function of Γ with $\gamma/\alpha = 1$ at $x = 0.59$ ($\rho(300) = 245 \mu\Omega \text{ cm}$) (**a**) and $x = 0.75$ ($\rho(300) = 203 \mu\Omega \text{ cm}$) (**b**). No choice of γ/α will cause the data to collapse onto a single function of Γ . These samples are far from optimal doping and have low superconducting transition temperatures, and therefore lie in a region of the $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ phase diagram that is known to be Fermi-liquid-like².

high- T limit (at zero field) of the resistivity as it is when extrapolated from the high- H limit (at low- T) of the MT, suggesting $\rho(0, 0)$ is a simple offset to the part of the resistance described by equation (1).

The magnetoresistance of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ is H -linear only at low temperatures and very near optimal doping, but the MT is consistent with equation (1) even at elevated temperatures for a range of compositions. This can be seen by plotting all of the MT curves together as a function of Γ (with γ determined from sample S1). As shown in Fig. 2, $\rho(\Gamma)$ asymptotically approaches a single line, as if there is a limiting rate at which the resistivity can increase as a function of Γ . However, we note that the approach to the Γ -linear dependence is non-universal, and possibly related to the Fermi liquid to non-Fermi liquid crossover discussed in other work^{2,24}. At still higher phosphorus content, there is no sign of the asymptotic behaviour for the magnetic fields available, as shown in Fig. 3, exactly as expected in ordinary metals²⁶.

H -linear MT can have many origins^{26–28}, particularly in complex multiband systems. However, any orbital MT mechanism will depend on the effective mass, which strongly diverges near optimal doping^{18,22–24}, and this in turn should be reflected as a strong variation of the MT. In contrast, we observe the same asymptotic MT response in this range of compositions. Moreover, our experimental observation of $\alpha/\gamma \approx 1$ suggests that the magnetic field sets an energy scale in the transport that is similar to that set by temperature. Although the microscopic nature of this scale is unknown, it is interesting that if one took the Zeeman energy of these materials ($g = 2, S = 1/2$; ref. 29) to be the relevant energy scale, one expects $\alpha/\gamma = 1$. Finally, we note that despite the apparent generality of

equation (1), it may not apply straightforwardly in other exotic metals that show T -linear resistivity. For example, significant disorder generally dampens MT effects and could provide a competing energy scale, obscuring the physics responsible for equation (1). Interestingly, however, existing MT data on other systems^{4,30} may be consistent with equation (1) (see Supplementary Information), motivating investigations of H/T scaling in other materials.

The form of the scaling observed in the MT of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ suggests that the H -linear behaviour has the same origin as the T -linear behaviour. The hypothesis that this is the result of critical physics is appealing, because the absence of an intrinsic transport energy scale could provide a general mechanism for the relaxation rate to scale with external parameters. This would be consistent with previous reports of quantum criticality in these compounds^{2,19–24} and might also explain the form of equation (1), where H and T compete to set the relaxation rate. If this is so, it would open a new route for the exploration of the quantum criticality using high magnetic fields. In any case, the relationship between the field and temperature dependencies of the resistivity is an important new clue towards our future understanding of the strange metal state in high-temperature superconductors and related strongly correlated metals.

The data that support the plots within this paper and other findings of this study are available from the corresponding author, J.G.A., upon reasonable request.

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Author contributions

I.M.H., J.G.A., A.S. and R.D.M. conceived the experiment and performed the analysis. I.M.H., T.H. and J.G.A. synthesized the samples. I.M.H., J.G.A., R.M.D., M.W., T.H. and N.P.B. performed the measurements at high magnetic fields. P.J.W.M. prepared the overdoped samples for transport measurements. All authors participated in the writing of the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.G.A.

Competing financial interests

The authors declare no competing financial interests.