Magnetoresistance Scaling Reveals Symmetries of the Strongly Correlated Dynamics in $BaFe_2(As_{1-x}P_x)_2$

Ian M. Hayes,[1,2] Zeyu Hao,[1] Nikola Maksimovic,[1,2] Sylvia K. Lewin,[1,2] Mun K. Chan,[3] Ross D. McDonald,[3] B. J. Ramshaw,[3,4] Joel E. Moore,[1,2] and James G. Analytis[1,2,*]

[1]*Department of Physics, University of California, Berkeley, California 94720, USA*
[2]*Lawrence Berkeley National Laboratory, Materials Science Division, Berkeley, California 94720, USA*
[3]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[4]*Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14853, USA*

(Received 22 May 2018; revised manuscript received 23 August 2018; published 9 November 2018)

The phenomenon of T-linear resistivity commonly observed in a number of strange metals has been widely seen as evidence for the breakdown of the quasiparticle picture of metals. This study shows that a recently discovered H/T scaling relationship in the magnetoresistance of the strange metal $BaFe_2(As_{1-x}P_x)_2$ is independent of the relative orientations of current and magnetic field. Rather, its magnitude and form depend only on the orientation of the magnetic field with respect to a single crystallographic axis: the direction perpendicular to the magnetic iron layers. This finding suggests that the magnetotransport scaling does not originate from the conventional averaging or orbital velocity of quasiparticles as they traverse a Fermi surface, but rather from dissipation arising from two-dimensional correlations.

DOI: 10.1103/PhysRevLett.121.197002

Many high-temperature superconductors exhibit strange metallic behavior in their normal state. This behavior is common to both the copper- and iron-based superconductors, and it has several accepted experimental signatures [1]; in the charge transport sector, these include a T-linear resistivity down to low temperatures and a temperature-dependent Hall effect. There is not, however, any widely accepted theory for the strange metal state. Although it is generally agreed that a successful description will involve some physics beyond the standard picture of metals, Landau's theory of the Fermi liquid [2], ideas have varied widely about what that additional component ought to be [3–9]. In this environment, experiments that can identify general features of the new physics, and especially symmetry information regarding the dominant scattering mechanisms, are invaluable.

The magnetic field dependence of the resistivity (MR) has occasionally been included in the strange metal phenomenology because the MR in these compounds is known to violate the scaling relationship between H and $\rho(H = 0)$, known as Kohler's rule, that is expected in a simple metal [10,11]. However, even within a quasiparticle picture there are many reasons why Kohler's rule could be violated, including the existence of multiple scattering times on different Fermi surface sheets or of a temperature or wavelength dependence of the scattering objects, including phonons. In any case, no single simple pattern has been observed in the MR that could guide theoretical efforts. Recently, we reported an anomalous scaling relationship between magnetic field and temperature in the MR of the unconventional high-T_c iron-pnictide superconductor $BaFe_2(As_{1-x}P_x)_2$ near optimal doping [12]. The existence of scaling between H and T in the MR is intriguing both because it is difficult to obtain in a Fermi liquid picture and because it connects the physics of T-linear resistivity to the effects of a magnetic field, providing a new window into the strange metal state. In particular, it was found that field has the same scaling dimension as temperature, leading to an H-linear MR at low temperatures with a gradient that is related to the gradient in temperature by the simple ratio of fundamental constants μ_B/k_B. However, this is exactly the right energy scale for Zeeman coupling to play an important role, which suggested that the scaling may still be driven by single-particle physics.

In this Letter, we leverage the vector nature of the magnetic field to reveal several important facts about the microscopics of the strange metal state. We find that the scaling magnetoresistance cannot be exclusively due to the conventional effects of quasiparticle orbits around the Fermi surface nor to the coupling of the magnetic field to individual spins, but must originate in some collective dynamics in the system. Furthermore, these dynamics must be strongly two-dimensional because the scaling behavior sees exclusively the c-axis component of an applied magnetic field. On the other hand, it must still couple equally to a current in any direction because the interlayer resistivity ρ_c and the in-plane resistivity ρ_{ab} show identical scaling behavior in both form and magnitude. These observations pose a challenge for theories of unconventional quantum dynamics in which the same degrees of freedom underlie both magnetic response and transport, whether two- or three-dimensional, as it would be unnatural for such degrees of freedom to respond highly anisotropically to field but behave isotropically with regard to current direction. Our results are consistent with an anisotropic, collective magnetic response that modifies the lifetime of current carriers in all directions.

Single crystals of $BaFe_2(As_{1-x}P_x)_2$ were grown by a self-flux method described elsewhere [13]. The phosphorous content of these materials was previously determined using x-ray photoelectron spectroscopy. Samples for this study were taken from the same or similar batches and found to have the anticipated T_c, which correlates well with the phosphorous fraction x. For ρ_c measurements, small platelike crystals with typical dimensions of $150 \times 150 \times (50\text{–}90)$ μm ($a \times b \times c$) were contacted by covering each ab face with tin-lead solder, as was done in previous studies of the interlayer resistivity in these materials [14]. These contacts had very small (10–50 $\mu\Omega$) resistances, which represent a small fraction (1%) of the sample signal. This allowed us to measure ρ_c by performing a four-point ac lock-in resistance measurement of the contact-sample-contact system and neglecting the contribution from the contacts. For ρ_{ab} measurements, a standard four-point measurement was used, with contacts made by first sputtering gold onto the contact areas and then attaching 25 μm gold wires with Epotek H20e silver epoxy. Measurements were performed in pulsed magnetic fields of up to 65 T at the NHMFL Pulsed Field Facility, Los Alamos National Laboratory.

For the interlayer resistivity ρ_c, we report measurements of the MR near optimal doping ($x \sim 0.3$) for both the longitudinal (H parallel to c) and transverse (H parallel to a) configurations. Figure 1 shows the data for the first of these configurations, from which two facts are immediately apparent. First, the MR is linear in field at the lowest temperatures and gradually develops curvature at higher temperatures and especially at lower fields [see Fig. 1(b)]. Second, it is almost temperature independent for low temperatures and high fields, as if the value of the magnetic field were the only important variable for determining the resistivity. These are the two most visible consequences of the scaling form found for the resistivity of ρ_{ab} [12]. Since the resistivity is linear in field at low temperatures, we can extrapolate that curve to zero field to obtain the residual resistivity and perform a scaling analysis on the temperature- or field-dependent part of the resistivity. Figure 1(c) shows the results of this analysis, where the data collapse onto a single, hyperbolalike curve.

The collapse of the data observed in Fig. 1 shows that ρ_c has the same qualitative behavior in H and T as the in-plane resistivity ρ_{ab} [12]. The quantitative details of the data are similar as well. Considered as a fraction of the zero field resistivity, the MR is of the same scale in ρ_c and ρ_{ab} at low temperatures. Below 30 K there is no normal state resistivity in zero field to compare to, but at 30 K the MR of ρ_c at 60 T is 27%, while for the same values of H and T it is 36% in ρ_{ab} [12]. This similarity is especially significant given that ρ_c is about 5 times larger than ρ_{ab}. The other important quantity that goes into the MR scaling is the scale factor connecting H and T. This can be found by comparing the $H/T = 0$ intercept of the hyperbola in Fig. 1(c) to the slope of the hyperbola at high values of H/T. In ρ_{ab} this quantity is found to be equal to μ_B/k_B to within a few percent [12]. In ρ_c this quantity is found to be about 5% smaller, but this difference is within the error of the fit. Taken together, these data show an interlayer magnetoresistance nearly identical to that seen in ρ_{ab} in form and magnitude.

It is highly unusual for the MR to be independent of current direction [15]. In an ordinary Fermi liquid, the effect of a magnetic field on the resistivity comes

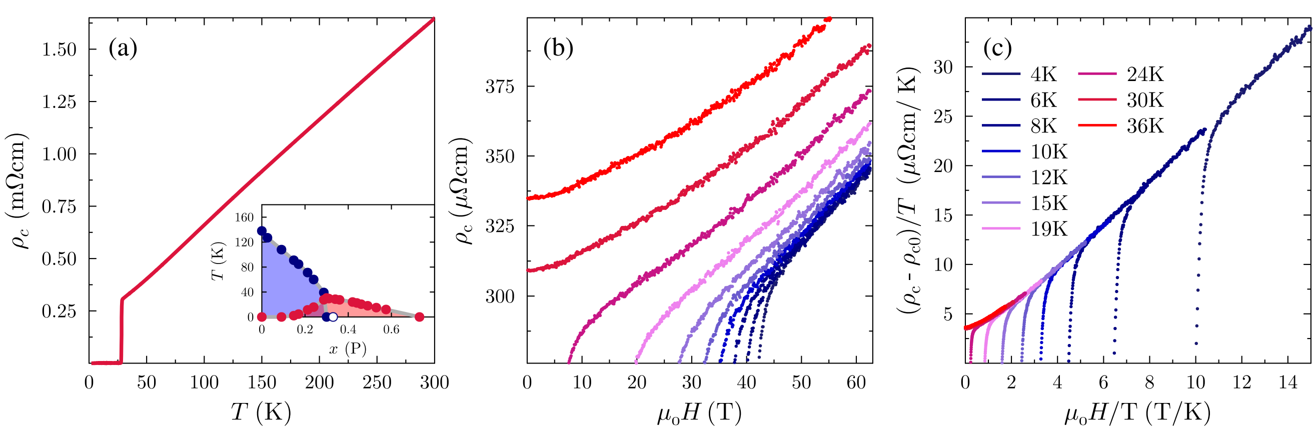

FIG. 1. Scaling in ρ_c of $BaFe_2(As_{1-x}P_x)_2$. (a) The interlayer resistivity ρ_c as a function of temperature. (Inset) A schematic phase diagram of $BaFe_2(As_{1-x}P_x)_2$, showing the AFM and superconducting transitions and the location of optimal doping (white circle). (b) Interlayer resistivity as a function of magnetic field up to 63 T at temperatures ranging from 4 to 36 K. The H-linear MR is apparent at low temperatures where ρ is roughly independent of T. (c) A scaling plot of the MR curves shown in (b). The residual resistivity (found by fitting the 4 K curve to a line and taking the $H = 0$ intercept) is subtracted off and the remainder is normalized to the temperature and plotted versus H/T.

principally from the action of the Lorentz force on the current-carrying quasiparticles. Under the influence of an electric field, the Fermi sea shifts and a net current comes from the excess of quasiparticles with momentum in one direction. If a magnetic field is also applied, the excited quasiparticles are deflected around the Fermi surface, reducing their average velocity in the direction of current flow and therefore reducing the corresponding conductivity. Because this reduction of the quasiparticle velocity depends on the sign and magnitude of the curvature of the Fermi surface, and because there is a different component of the Fermi velocity that is relevant for ρ_{ab} and ρ_c, this process is usually exquisitely sensitive to the relative angles of the field, current, and crystallographic axes. Indeed, the angular dependence of the MR has historically been a powerful way to map the shape of the Fermi surface in ordinary metals, even without the observation of Shubnikov–de Haas oscillations [15]. This is not to say that MR cannot appear to be comparable in magnitude for $H//c//i$ and $H//c\perp i$, as indeed it does in systems with appropriate interlayer warping [16]. It is the indifference of the MR scaling in both form and magnitude to current direction observed here that suggests an origin that is more complex than the cyclotron motion of quasiparticles under the action of the Lorentz force.

This is the first major finding of this study, and it is intriguing because it supports the idea that the dynamics of quasiparticles do not dominate the transport properties of these materials. It also naturally raises the question of whether the scaling is independent of field orientation as well. There are three further field-current-crystal orientations to consider: the longitudinal MR of ρ_{ab}, the transverse MR of ρ_{ab} with field in the plane [Fig. 2(a)], and the transverse MR of ρ_c. There is only one transverse MR for ρ_c because $BaFe_2(As_{1-x}P_x)_2$ is tetragonal at optimal doping. With field along the a-axis H_{C2} is around 60 T, leaving almost no normal state accessible at the lowest temperatures. However, since the object of interest in these measurements is a scaling relation in H and T, it should still be observable in a 65 T magnet.

The two configurations of transverse MR with field in the plane show broadly similar behavior and show clear differences with the MR for H aligned with the c axis [Figs. 2(a) and 2(b)]. First, the overall scale of the MR is much smaller: 4% at 30 K and 60 T. Second, although there is not enough normal state at low temperatures to make a definitive statement about linearity, it is clear that the resistivity is not independent of temperature at high fields, which immediately tells us that the data do not scale in the same manner as those taken with the field along the c axis. Scaling analyses confirm this intuition. Therefore, H/T scaling seems to be a special property of the charge transport when the magnetic field is normal to the iron-arsenide plane.

To test whether the c-axis component of the magnetic field really is the only relevant part for the scaling, we measured the angle dependence of ρ_{ab}. Figure 3 shows the in-plane resistivity as a function of H as the field is rotated from the out-of-plane orientation to the in-plane orientation, all the while remaining orthogonal to the current. These data were taken at 10 K; this temperature was chosen to be low enough for the MR to be H-linear, but not so low that the upper critical field would prevent us from measuring anything for large angles. The H-linear MR is present for small deviations from the scaling configuration, but its slope decreases at higher angles. Significantly, the extrapolated intercepts of these low-angle curves are all the same [Fig. 3(a)], suggesting that we are seeing the same H-linear MR, but with a smaller effective field. To see this, we can plot these curves against the quadrature sum of $H_c = H\cos(\theta)$ and T, $\Gamma_c \equiv \sqrt{(k_B T)^2 + (\mu_B \mu_0 H_c)^2}$. As shown in Fig. 3(b), this causes a remarkable collapse of the data at low angles. The scaling in the MR therefore follows the c-axis component of the magnetic field and only this component.

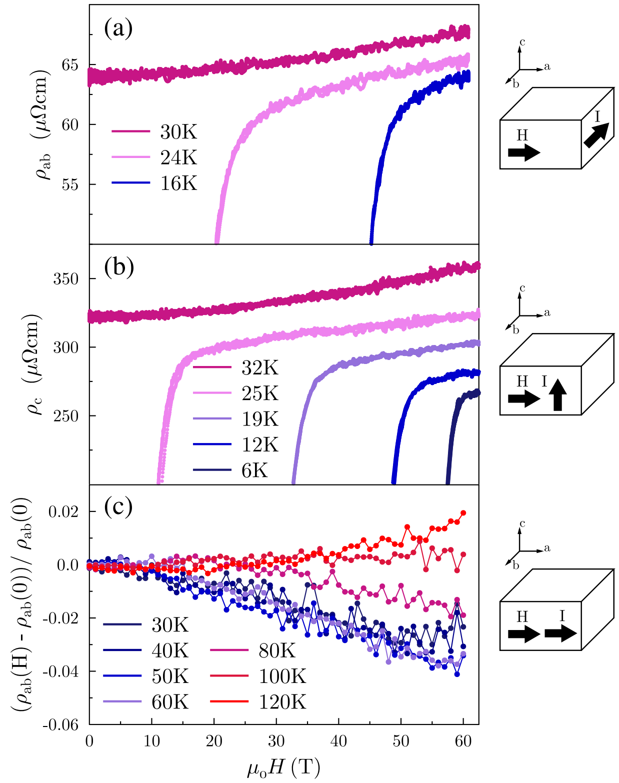

FIG. 2. MR of $BaFe_2(As_{1-x}P_x)_2$ in ρ_{ab} and ρ_c with H in the plane. (a) MR of ρ_{ab} as a function of transverse (in-plane) magnetic field up to 63 T at temperatures ranging from 4 to 36 K. Although H_{C2} is very close to 60 T, we can see that there is still strong temperature dependence at high fields, and thus H-T scaling of the form found with field along the c axis is not present. (b) The same plot but for ρ_c. (c) Fractional MR of ρ_{ab} in the longitudinal configuration. Below about 100 K the MR becomes negative and has a similar magnitude to the transverse in-plane configuration. Diagrams on the right are schematic representations of each experimental configuration.

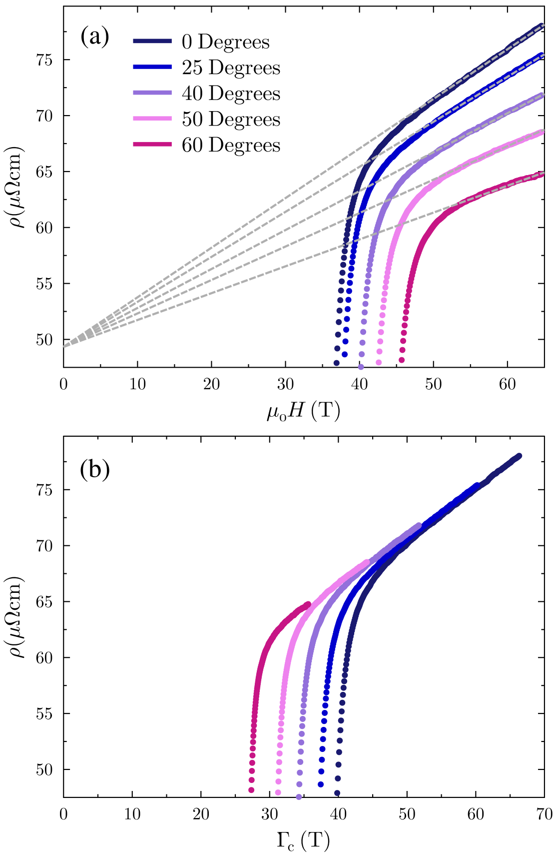

FIG. 3. Transverse MR of ρ_{ab} and with H rotated away from the c axis. (a) Raw MR at 10 K as a function of H for several orientations of the magnetic field. The field was always maintained perpendicular to the current but rotated away from the c axis by the amount shown. (b) The same curves plotted in panel (A), but this time as a function of the combined field-temperature energy scale, Γ_c, using only the component of the field along the c axis.

There is one final configuration of field and current: longitudinal MR in the plane. Interestingly, the MR in this configuration is negative with a non-negligible magnitude of about 4% (comparable in magnitude to the positive MR in the transverse in-plane configuration). The negative longitudinal magnetoresistance is strongly temperature dependent, turning on around 100 K, approximately where the resistivity starts to deviate from strict T-linear behavior [Fig. 1(a)]. Negative MR in a metal with a large Fermi surface is highly unusual, even in the longitudinal configuration. General considerations lead us to expect that an applied magnetic field will increase the resistivity since it will deflect quasiparticles away from the direction of the current [17]. A negative MR can occur naturally, however, if the dominant scattering objects are magnetic, since one effect of an applied magnetic field can be to slow or freeze magnetic degrees of freedom.

The observation that the scaling only appears for the magnetic field along the c axis demonstrates that the effect is not due to the coupling of field to individual spins, as such a strong anisotropy in Zeeman coupling is unlikely [18]. Additionally, the observation of the scaling for both in-plane and c-axis currents rules out most straightforward cyclotron effects, as those are generally sensitive to the relative orientation of current, Fermi velocity, and magnetic field. Thus, the MR of $BaFe_2(As_{1-x}P_x)_2$ is not the naive response of single particles under the action of the Lorentz force. Although correlation effects are often invoked to explain the T-linear resistivity widely observed in strange metals, there has not, to our knowledge, been a simple experimental observation that not only suggests their existence but reveals information about their symmetry properties. The connection of the phenomenon of T-linear resistivity to the H/T MR scaling allows us to determine that these correlations have a two-dimensional coupling to applied magnetic fields (that does not arise from the Fermi surface), but also an isotropic coupling to current-carrying excitations.

A small number of models attempting to explain the observed MR scaling have only recently started to emerge, and the present results should inform these studies [19,20]. Specifically, models of strange metal behavior that depend on Fermi surface details, like hot spots, are unlikely in light of the present results since they depend strongly on the relative direction of the Fermi velocity and the applied field [21,22]. On the other hand, models that begin from non-Fermi-liquid starting points, including Sachdev-Ye-Kitaev lattice models [23], must find ways to include anisotropies in their magnetic response. This could be achieved by explicitly introducing two types of degrees of freedom, as some recent extensions of these models have done [24].

Notably, the scaling is observed on the disordered side of a quantum phase transition to in-plane AFM order [inset of Fig. 1(a)]. It seems probable that the collective magnetic response is related to magnetic fluctuations of this in-plane order, which are expected to be more sensitive to transverse (i.e., c-axis) fields. In the ordered state, it is known that the magnetic response is highly anisotropic [25]. Hence, the coupling of conduction electrons to collective magnetic fluctuations across a range of length scales should be included in models of the observed scaling behavior. This coupling emerges naturally in approaches to the strange metal state that are based on critical fluctuations of an order parameter, including the marginal Fermi liquid theory [4,26]. Interestingly, a number of other strange metals like heavy fermion and cuprate superconductors are also associated with strongly 2D correlations, and this connection may be important to explaining their common properties, particularly T-linear resistivity.

We thank Chandra Varma, Philip Phillips, Aavishkar Patel, and Subir Sachdev for fruitful discussions. This work was supported by the Gordon and Betty Moore Foundation's EPiQS Initiative through Grant No. GBMF4374. Materials synthesis was supported as part of the Center for Novel Pathways to Quantum Coherence in Materials, an Energy

Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Basic Energy Sciences. A portion of this work was performed at the National High Magnetic Field Laboratory, which is supported by National Science Foundation Cooperative Agreement No. DMR-1157490 and No. DMR-1644779 and the State of Florida. B. R., M.-K. C., and R. D. M. acknowledge funding from the U.S. Department of Energy Office of Basic Energy Sciences Science at 100 T program. S. K. L. acknowledges support from the National Science Foundation Graduate Research Fellowship under Grant No. DGE 1106400. J. E. M. acknowledges the support of the Quantum Materials program at Lawrence Berkeley National Laboratory, which is supported by the Director, Office of Science, Office of Basic Energy Sciences, Materials Sciences and Engineering Division of the U.S. Department of Energy under Award No. DE-AC02-05CH11231.

*Corresponding author.
analytis@berkeley.edu

[1] G. R. Stewart, Non-Fermi-liquid behavior in d- and f-electron metals, Rev. Mod. Phys. **73**, 797 (2001).
[2] L. Landau, The theory of a Fermi liquid, J. Exp. Theor. Phys. **3**, 920 (1957).
[3] P. A. Casey and P. W. Anderson, Hidden Fermi Liquid: Self-Consistent Theory for the Normal State of High-T_c Superconductors, Phys. Rev. Lett. **106**, 097002 (2011).
[4] C. M. Varma, Quantum-critical fluctuations in 2D metals: Strange metals and superconductivity in antiferromagnets and in cuprates, Rep. Prog. Phys. **79**, 082501 (2016).
[5] S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu, Fluctuating spin density waves in metals, Phys. Rev. B **80**, 155129 (2009).
[6] S. A. Hartnoll, Theory of universal incoherent metallic transport, Nat. Phys. **11**, 54 (2015).
[7] D. Dalidovich and P. Phillips, Nonlinear Transport Near a Quantum Phase Transition in Two Dimensions, Phys. Rev. Lett. **93**, 027004 (2004).
[8] A. G. Green and S. L. Sondhi, Nonlinear Quantum Critical Transport and the Schwinger Mechanism for a Superfluid-Mott-Insulator Transition of Bosons, Phys. Rev. Lett. **95**, 267001 (2005).
[9] R. A. Davison, K. Schalm, and J. Zaanen, Holographic duality and the resistivity of strange metals, Phys. Rev. B **89**, 245116 (2014).
[10] J. M. Harris, Y. F. Yan, P. Matl, N. P. Ong, P. W. Anderson, T. Kimura, and K. Kitazawa, Violation of Kohler's Rule in the Normal-State Magnetoresistance of $YBa_2Cu_3O_{7-\delta}$ and $La_{2-x}Sr_xCuO_4$, Phys. Rev. Lett. **75**, 1391 (1995).
[11] S. Kasahara, T. Shibauchi, K. Hashimoto, K. Ikada, S. Tonegawa, R. Okazaki, H. Shishido, H. Ikeda, H. Takeya, K. Hirata, T. Terashima, and Y. Matsuda, Evolution from non-Fermi- to fermi-liquid transport via isovalent doping in $BaFe_2(As_{1-x}P_x)_2$ superconductors, Phys. Rev. B **81**, 184519 (2010).
[12] I. M. Hayes, R. M. McDonald, N. P. Breznay, T. Helm, P. J. W. Moll, M. Wartenbe, A. Shekhter, and J. G. Analytis, Scaling between magnetic field and temperature in the high temperature superconductor $BaFe_2(As_{1-x}P_x)_2$, Nat. Phys. **12**, 916 (2016).
[13] J. G. Analytis, J. H. Chu, R. D. McDonald, S. C. Riggs, and I. R. Fisher, Enhanced Fermi-Surface Nesting in Superconducting $BaFe_2(As_{1-x}P_x)_2$ Revealed by the De Haas—van Alphen Effect, Phys. Rev. Lett. **105**, 207004 (2010).
[14] M. A. Tanatar, K. Hashimoto, S. Kasahara, T. Shibauchi, Y. Matsuda, and R. Prozorov, Interplane resistivity of isovalent doped $BaFe_2(As_{1-x}P_x)_2$, Phys. Rev. B **87**, 104506 (2013).
[15] A. B. Pippard, *Magnetoresistance in Metals*, 1st ed. (Cambridge University Press, Cambridge, England, 2009).
[16] N. E. Hussey, A. P. Mackenzie, J. R. Cooper, Y. Maeno, S. Nishizaki, and T. Fujita, Normal-state magnetoresistance of Sr2RuO4, Phys. Rev. B **57**, 5505 (1998).
[17] A. B. Pippard, Longitudinal magnetoresistance, Proc. R. Soc. A **282**, 464 (1964).
[18] H.-A. Krug von Nidda, S. Kraus, S. Schaile, E. Dengler, N. Pascher, M. Hemmida, M. J. Eom, J. S. Kim, H. S. Jeevan, P. Gegenwart, J. Deisenhofer, and A. Loidl, Electron spin resonance in Eu-based iron pnictides, Phys. Rev. B **86**, 094411 (2012).
[19] L. Zou, S. Lederer, and T. Senthil, Theory of anomalous magnetotransport from mass anisotropy, Phys. Rev. B **95**, 245135 (2017).
[20] A. A. Patel, J. McGreevy, D. P. Arovas, and S. Sachdev, Magnetotransport in a Model of a Disordered Strange Metal, Phys. Rev. X **8**, 021049 (2018).
[21] A. Rosch, Magnetotransport in nearly antiferromagnetic metals, Phys. Rev. B **62**, 4945 (2000).
[22] A. E. Koshelev, Magnetotransport of multiple-band nearly antiferromagnetic metals due to hot-spot scattering, Phys. Rev. B **94**, 125154 (2016).
[23] S. Sachdev and J. Ye, Gapless Spin-Fluid Ground State in a Random Quantum Heisenberg Magnet, Phys. Rev. Lett. **70**, 3339 (1993).
[24] D. Chowdhury, Y. Werman, E. Berg, and T. Senthil, Translationally Invariant Non-Fermi-Liquid Metals with Critical Fermi Surfaces: Solvable Models, Phys. Rev. X **8**, 031024 (2018).
[25] J.-H. Chu, J. G. Analytis, K. De Greve, P. L. McMahon, Z. Islam, Y. Yamamoto, and I. R. Fisher, In-plane resistivity anisotropy in an underdoped iron arsenide superconductor, Science **329**, 824 (2010).
[26] C. M. Varma, P. B. Littlewood, S. Schmitt-Rink, E. Abrahams, and A. E. Ruckstein, Phenomenology of the Normal State of Cu-O High-Temperature Superconductors, Phys. Rev. Lett. **63**, 1996 (1989).