

Quantum Critical Point in the Itinerant Ferromagnet $\text{Ni}_{1-x}\text{Rh}_x$

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We report a chemical substitution-induced ferromagnetic quantum critical point in polycrystalline $\text{Ni}_{1-x}\text{Rh}_x$ alloys. Through magnetization and muon spin relaxation measurements, we show that the ferromagnetic ordering temperature is suppressed continuously to zero at $x_{\text{crit}} = 0.375$ while the magnetic volume fraction remains 100% up to x_{crit} , pointing to a second order transition. Non-Fermi liquid behavior is observed close to x_{crit} , where the electronic specific heat C_{el}/T diverges logarithmically, while immediately above x_{crit} the volume thermal expansion coefficient α_V/T and the Grüneisen ratio $\Gamma = \alpha_V/C_{\text{el}}$ both diverge logarithmically in the low temperature limit, further indication of a ferromagnetic quantum critical point in $\text{Ni}_{1-x}\text{Rh}_x$.

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A quantum critical point (QCP) occurs when a phase transition is continuously suppressed to zero temperature. The intense quantum fluctuations in the vicinity of a QCP profoundly alter a material's electronic properties, resulting in non-Fermi liquid behavior and, in some cases, unconventional superconductivity [1,2]. The most ubiquitous QCP separates an antiferromagnetically ordered state from one in which quantum fluctuations disrupt the order. Notable examples are found among heavy fermion systems [1,3,4]. QCPs in ferromagnetic (FM) metals have proven far more elusive [5]. It is now understood that a FM QCP is inherently unstable and can survive only in rare circumstances [6]. In this Letter, we report the discovery of a FM QCP in $\text{Ni}_{1-x}\text{Rh}_x$, as evidenced by (i) a second-order phase transition up to the critical concentration x_{crit} , and (ii) divergence of the electronic specific heat coefficient C_{el}/T , the volume thermal expansion α_V/T , and the Grüneisen ratio $\Gamma = \alpha_V/C_{\text{el}}$. The dilution of the d -electron magnetic sublattice as the tuning parameter to induce a FM QCP opens a new route for exploring FM quantum criticality and possible new collective phases near the QCP, such as unconventional superconductivity [7].

FM QCPs are revealed via chemical substitution in $\text{Zr}_{1-x}\text{Nb}_x\text{Zn}_2$ [8], $\text{SrCo}_2(\text{Ge}_{1-x}\text{P}_x)_2$ [9], $\text{YbNi}_4(\text{P}_{1-x}\text{As}_x)_2$ [10], and $(\text{Sc}_{1-x}\text{Lu}_x)_{3.1}\text{In}$ [11]. The disorder effect is minimal or negligible in these systems. For $\text{SrCo}_2(\text{Ge}_{1-x}\text{P}_x)_2$, the

QCP is induced by the breaking of dimers [9]. However, the exact mechanism responsible for the FM QCP in the other three systems remains unclear. In most other FM metals, the QCP is preempted when the continuous (second-order) transition as a function of nonthermal control parameter either becomes discontinuous (first order), or the ferromagnetism is replaced by a spatially modulated ordered state [5,12–15]. Theoretical work by Belitz, Kirkpatrick, and Vojta (BKV) has proposed a route towards a FM QCP by long-range effective spin interactions that occur in the presence of quenched disorder [6,16,17]. A handful of FM QCPs have been identified as candidates for this phenomenology, including $\text{UCo}_{1-x}\text{Fe}_x\text{Ge}$ [18], $(\text{Mn}_{1-x}\text{Fe}_x)\text{Si}$ [19], NiCoCr_x [20], and $\text{Ce}(\text{Pd}_{1-x}\text{Ni}_x)_2\text{P}_2$ [21], where disorder is inherently introduced by the chemical substitution. In most of these systems, the proposed existence of a QCP is based on either divergence of some thermodynamic parameters [18,20,21] or the second-order nature of the transition [19]. However, the unambiguous identification of a QCP requires that both these criteria be fulfilled. This point is exemplified by disordered $\text{Sr}_{1-x}\text{Ca}_x\text{RuO}_3$, for which a QCP can be ruled out because the transition at $T = 0$ is first order [22], and yet, quantum critical scaling is still observed [23]. Thus, in order to unambiguously identify a FM QCP it is essential that both thermodynamic signatures of quantum fluctuations and second-order behavior be observed simultaneously. Our

observation of both these requisite signatures in a chemically simple material where the FM QCP is induced via direct dilution of its d electrons elevate $\text{Ni}_{1-x}\text{Rh}_x$ to a top tier of candidates.

Elemental Ni, which has a simple face-centered cubic structure, is known to order ferromagnetically below its Curie temperature $T_C = 627$ K [24]. Upon alloying with Rh, the T_C of $\text{Ni}_{1-x}\text{Rh}_x$ is quickly suppressed [25]. $\text{Ni}_{1-x}\text{Rh}_x$ has more configuration entropy than pure Ni [26]. Also, the metallic radii of Ni (124 pm) and Rh (134 pm) differ by $\sim 8\%$. Naturally, one would expect that, compared to pure Ni, there is more disorder in $\text{Ni}_{1-x}\text{Rh}_x$ alloy, making it a good candidate to test for the existence of a disorder-driven FM QCP. Polycrystalline $\text{Ni}_{1-x}\text{Rh}_x$ samples with $0.3 \leq x \leq 0.42$ were prepared by arc melting the constituents Ni and Rh and annealed at 1000°C . Magnetization measurements were carried out using a Quantum Design (QD) magnetic property measurement system. Zero-field muon spin relaxation measurements were performed at the M20 surface muon channel at TRIUMF. Specific heat was measured using a QD Dynacool physical property measurement system equipped with a dilution refrigerator. Thermal expansion was measured with a homemade capacitance dilatometer. More details about the sample characterizations and experimental methods are provided in the Supplemental Material [27–34].

Figure 1(a) shows the $\mu_0 H = 0.01$ T magnetic susceptibility $\Delta M(T)/H$ of $\text{Ni}_{1-x}\text{Rh}_x$, after a temperature-independent contribution M_0 was subtracted from the measured $M(T)$ ($\Delta M = M - M_0$). $\Delta M/H$ sharply increases as T is lowered through T_C for $x = 0.32$ – 0.36 where T_C is determined both through a linear fit, as shown in Fig. 1(a), and the Arrott-Noakes analysis as discussed below. For $x_{\text{crit}} = 0.375$ (where $T_C \rightarrow 0$), $\Delta M/H$ shows only a small increase down to the lowest measured temperature of 2 K, consistent with the complete suppression of FM order. Isothermal magnetization measurements at $T = 2$ K confirm that $\text{Ni}_{1-x}\text{Rh}_x$ is a soft ferromagnet without a measurable hysteresis [Fig. 1(b)]. We cannot rule out a very small antiferromagnetic component or canting close to x_{crit} , although magnetization suggests that FM correlations dominate, as evidenced by an abrupt increase of $M(H)$ at the lowest field [Fig. 1(b)] and adherence to Arrott-Noakes scaling all the way up to x_{crit} . Future neutron scattering and nuclear magnetic resonance measurements will shed light on this issue. For the $x = 0.32$ sample, which orders near 100 K, the inverse magnetic susceptibility $H/\Delta M$ exhibits Curie-Weiss-like behavior between 150 and 300 K, from which we derive a paramagnetic (PM) effective moment $\mu_{\text{PM}} = 1.97 \mu_B/\text{f.u.}$ (see the Supplemental Material [27]). For the same sample, ΔM is small at 7 T ($\sim 0.22 \mu_B/\text{f.u.}$), and the Rhodes-Wohlfarth ratio, $\mu_{\text{PM}}/\mu_{\text{sat}} = 9$, much larger than unity, is indicative of itinerant moment behavior in $\text{Ni}_{1-x}\text{Rh}_x$ [35].

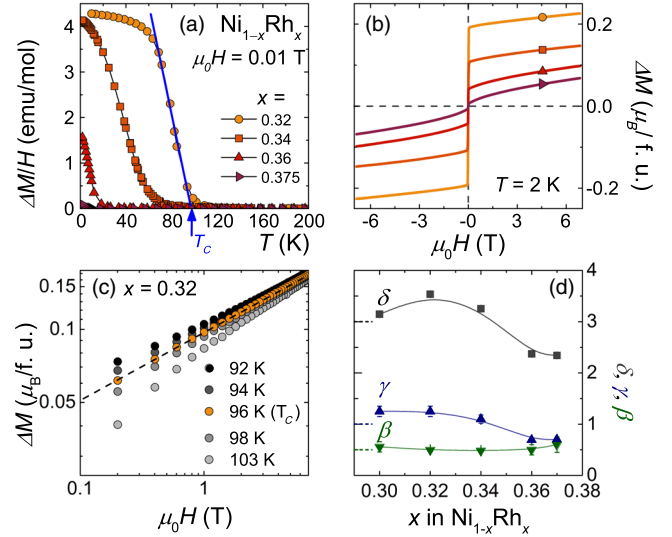


FIG. 1. (a) Magnetic susceptibility $\Delta M/H = (M - M_0)/H$ for $\mu_0 H = 0.01$ T and (b) isothermal magnetization ΔM at $T = 2$ K of $\text{Ni}_{1-x}\text{Rh}_x$. Solid line in (a) shows how T_C was determined. (c) Log-log magnetization isotherms for $x = 0.32$, with the dashed line showing T_C . (d) Critical exponents β , γ , and δ determined from the Arrott-Noakes scaling plots as a function of x . Solid lines are guides to the eye. Mean-field values $\beta = 0.5$, $\gamma = 1$, and $\delta = 3$ are indicated by horizontal dashed lines.

An earlier study indicated spin glass behavior in $\text{Ni}_{1-x}\text{Rh}_x$ [36]. However, our ac magnetic susceptibility measurements, presented in the Supplemental Material [27], show no evidence for spin glass behavior near T_C . Such a discrepancy may be due to different purity of starting materials or sample homogeneity.

For ferromagnets, the equation of state at T_C is given by $\Delta M \sim H^{1/\delta}$ [31]. From linear fits of $\log(\Delta M)$ vs $\log(\mu_0 H)$, as shown by the dashed line in Fig. 1(c), we determine that $T_C = 96$ K and $\delta \sim 3.5$ for the $x = 0.32$ sample. We applied the same analysis for all samples with $x = 0.30$ – 0.37 . The critical exponents β and γ were determined by applying Arrott-Noakes scaling to the isotherms measured in the vicinity of T_C (see the Supplemental Material [27] for details) [31]. The composition dependence of all three exponents, δ , β , and γ , is summarized in Fig. 1(d). The Widom relation $\gamma/\beta = \delta - 1$ is obeyed over the entire range of Rh concentrations investigated here, a self-consistent check of the scaling analysis. At $x = 0.30$, which is well below x_{crit} , the exponents $\beta = 0.5$, $\gamma = 1.3$, and $\delta = 3.1$ are close to the expected mean-field values. With increasing x , the exponents deviate from the mean-field values and approach $\beta = 0.6$, $\gamma = 0.7$, and $\delta = 2.3$ at $x = 0.37$, just below x_{crit} . A similar evolution of the critical exponents with chemical substitution was observed in $\text{Sr}_{1-x}\text{Ca}_x\text{RuO}_3$, where it was proposed that disorder resulted in enhanced quantum fluctuations near x_{crit} [37].

Zero field μSR measurements were performed on six samples of $\text{Ni}_{1-x}\text{Rh}_x$ with $x = 0.30$ – 0.39 , in order to

determine whether the magnetic order takes place via a first- or second-order process. Hallmarks of a first-order transition are phase separation or an abrupt change of ground state [22,38]. Conversely, in the case of a second-order transition, the size of the ordered moment is expected to continuously decrease without phase separation. μ SR allows an independent measure of both the local order parameter and the magnetic volume fraction, f_{mag} , and can thus unambiguously distinguish between these scenarios. Representative muon decay asymmetry spectra, $P(t)$, are plotted in Fig. 2(a) for $x = 0.32$ at various temperatures below and above $T_C = 96$ K. Above T_C , $P(t)$ is essentially nonrelaxing, as expected in a PM state. The onset of magnetic order is signaled by a fraction of the asymmetry undergoing rapid relaxation at early times. The compositional dependence of $P(t)$ at $T = 2$ K is presented in Fig. 2(b). This comparison reveals that the samples with the highest Rh concentrations, $x = 0.375$ and 0.39 ($\geq x_{\text{crit}}$, blue and purple symbols), exhibit only weak relaxation down to the lowest measured temperatures, thus confirming the absence of magnetic order for these compositions. The samples with $x < x_{\text{crit}}$ exhibit sharp relaxation associated with magnetic order. The $P(t)$ data for all compositions and temperatures is well-described by the dynamic Kubo-Toyabe function [32]:

$$P(t) = (1 - f_{\text{mag}})e^{-\lambda t} + f_{\text{mag}}G_{\text{DKT}}(t, \sigma, \nu), \quad (1)$$

where λ and σ are the relaxation rates for the nonmagnetic and magnetic fractions of the sample, respectively, and ν is the hopping rate. The temperature dependence of f_{mag} is presented in Fig. 2(c), revealing no evidence for phase

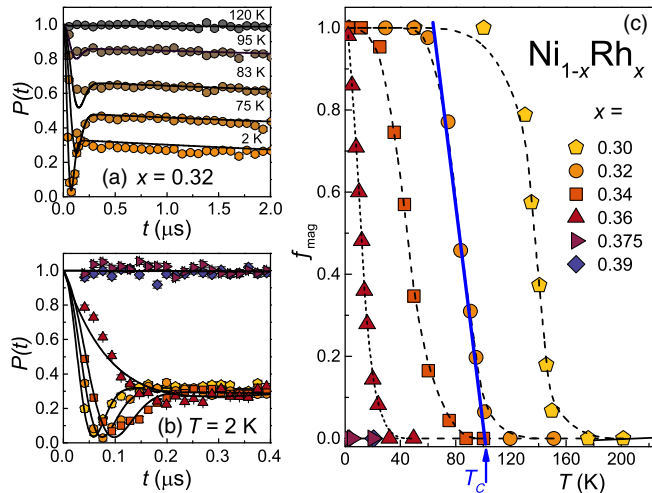


FIG. 2. (a) Temperature evolution of the normalized muon decay asymmetry $P(t)$ for $\text{Ni}_{1-x}\text{Rh}_x$ for $x = 0.32$. The solid lines are fits to Eq. (1). (b) $P(t)$ for all measured samples $x = 0.30$ – 0.39 , at $T = 2$ K. (c) The magnetic volume fraction f_{mag} as a function of temperature. Solid line shows how T_C was determined.

separation; f_{mag} remains 100% up to Rh concentrations of $x = 0.36$ and drops to 0% at $x_{\text{crit}} = 0.375$. With increasing Rh concentration, the Kubo-Toyabe minimum moves to increasing times as can be seen in Fig. 2(b), consistent with a decreasing ordered moment. This suggests that the suppression of magnetic order in $\text{Ni}_{1-x}\text{Rh}_x$ occurs via a continuous second-order process.

Next we show evidence for divergent thermodynamic parameters in $\text{Ni}_{1-x}\text{Rh}_x$. Figure 3(a) shows the electronic specific heat C_{el}/T around $x_{\text{crit}} = 0.375$, where the phonon contribution has been subtracted from the measured specific heat. For concentrations that are both far above and far below x_{crit} ($x \leq 0.15$ and $x \geq 0.6$), C_{el}/T is nearly temperature-independent at low temperatures, as expected for a Fermi liquid (FL) [27]. Close to x_{crit} , C_{el}/T diverges logarithmically on cooling. The fastest divergence occurs at $x_{\text{crit}} = 0.375$, where $C_{\text{el}}/T = a_0 \log(T_0/T)$ between 0.1 and 3 K [solid line in Fig. 3(a)], such that a_0 is maximum at the QCP (red diamonds in Fig. 4). This logarithmic divergence was previously reported in $\text{Ni}_{0.62}\text{Rh}_{0.38}$ [39] and has also been observed in other QCP systems [9–11,40]. For $x > x_{\text{crit}}$, C_{el}/T levels off at the lowest temperatures, consistent with non-Fermi-liquid (NFL) to

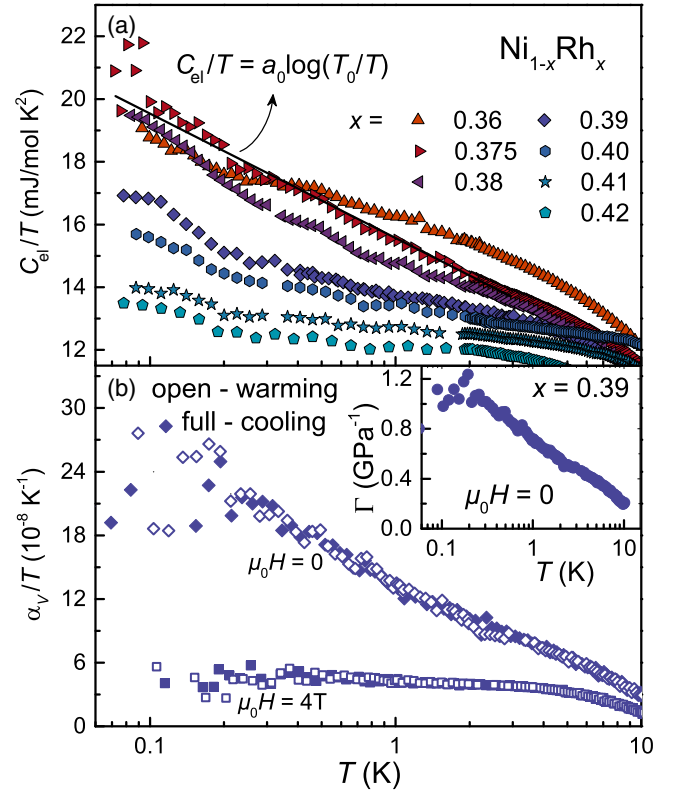


FIG. 3. (a) Temperature dependence of the electronic specific heat C_{el}/T for $\text{Ni}_{1-x}\text{Rh}_x$ with $x = 0.36$ – 0.42 . The solid line represents a fit to $C_{\text{el}}/T = a_0 \log(T_0/T)$ at $x_{\text{crit}} = 0.375$. (b) The volume thermal expansion coefficient α_v/T at $\mu_0 H = 0$ (diamonds) and 4 T (squares) for $\text{Ni}_{1-x}\text{Rh}_x$ with $x = 0.39$. The inset shows the Grüneisen ratio Γ vs T at $\mu_0 H = 0$.

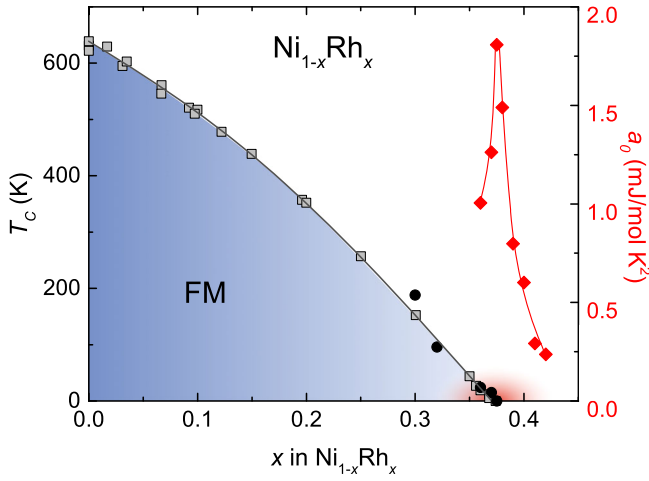


FIG. 4. $T_C - x$ phase diagram of $\text{Ni}_{1-x}\text{Rh}_x$. The blue region corresponds to long-range FM order. The red area marks the NFL behavior around the QCP. Black circles: T_C and red diamonds: the coefficient a_0 from the specific heat data (from current study). Gray squares: from Refs. [36,41–44].

FL crossover. This is similar to other FM and antiferromagnetic quantum critical systems [1,3–5].

QCPs are characterized by an accumulation of magnetic entropy S_{mag} as a function of the control parameter at low, but finite temperatures. In $\text{Ni}_{1-x}\text{Rh}_x$, this is underscored by the dependence of the specific heat parameter a_0 on x (red diamonds in Fig. 4), given that S_{mag} is commensurate to a_0 , which, in turn, is maximum at the QCP. At the same time, S_{mag} is related to the volume thermal expansion α_V through the Maxwell relation $\alpha_V = -V^{-1}\partial S_{\text{mag}}/\partial p$ (where p is pressure), and the divergence of α_V/T has been taken as proof of the QCP in heavy fermion systems, such as $\text{CeCu}_{6-x}\text{Au}_x$ [45], CeNi_2Ge_2 , and $\text{YbRh}_2(\text{Si}_{0.95}\text{Ge}_{0.05})_2$ [46]. Our data shows that at $x = 0.39$ (just above the QCP), zero-field α_V/T diverges logarithmically between 10 and 0.1 K [diamonds in Fig. 3(b)]. This is indicative of NFL behavior in proximity to the QCP [47]. The data show no hysteresis between heating (open) and cooling (full) measurements, ruling out any history-dependent spin glass effects. The length measurements on $\text{Ni}_{1-x}\text{Rh}_x$ with $x = 0.39$ reached the resolution limit of the dilatometer of $\Delta L \geq 10^{-3}$ Å at the lowest measured temperatures, resulting in an enhanced scattering below ~ 0.2 K. The application of a magnetic field of 4 T reduces α_V/T to a nearly constant value below 4 K, indicating a recovery of the FL behavior [squares in Fig. 3(b)]. This recovery of FL behavior is consistent with what has been observed in field-dependent specific heat measurements for $\text{Ni}_{0.62}\text{Rh}_{0.38}$ [39].

An additional probe for a QCP is the Grüneisen ratio $\Gamma = \alpha_V/C_{\text{el}} \sim 1/E^* \cdot \partial E^*/\partial p$. Γ reveals the hydrostatic pressure dependence of the dominating, characteristic energy scale E^* (e.g., the energy related to the conduction band splitting at the Fermi energy, which is proportional to

the spontaneous magnetization [48]). At a QCP, E^* vanishes, and Γ is expected to diverge with decreasing T [47]. In the low temperature range for the α_V measurements, the phonon contribution is negligible. The calculated Γ is depicted in the inset of Fig. 3(b), showing logarithmic divergence over two decades in temperature from $T = 10$ to 0.1 K. The fact that $\Gamma \sim -\log T$ suggests either that the quantum critical behavior in $\text{Ni}_{1-x}\text{Rh}_x$ extends to a finite pressure interval (rather than a point) [47], or that the system lies within a disordered quantum Griffiths phase [49].

We summarize the $T_C - x$ phase diagram of $\text{Ni}_{1-x}\text{Rh}_x$ in Fig. 4. Magnetization $M(T, H)$ and μSR measurements reveal the suppression of T_C with increasing Rh concentration up to $x_{\text{crit}} = 0.375$ (black symbols). The magnetically ordered volume fraction remains 100% up to x_{crit} , while the magnitude of the ordered moment per formula unit continuously decreases, as expected for a second order transition [19]. In addition, the FM QCP is also revealed by the divergence of C_{el}/T , α_V/T , and Γ in the low temperature limit, associated with NFL behavior that extends up to ~ 10 K.

Finally, we compare our results with other $\text{Ni}_{1-y}\text{M}_y$ ($M = \text{Al, Si, V, Cr, Mn, Cu, Zn, Pd, and Sb}$) alloys. Nonmagnetic M metals dilute the Ni magnetic moment and therefore suppress the FM order. Magnetic susceptibility measurements on these alloys are sensitive to sample preparation [36,50]. In the absence of a spin glass state or short range order, the enhancement of C_{el}/T has been observed for all M where $T_C \rightarrow 0$ [50–52]. This commonality can be understood in terms of enhanced spin fluctuations and does not necessarily indicate quantum critical fluctuations. A noteworthy member of this family is $\text{Ni}_{1-y}\text{V}_y$ where V substitution results in quantum Griffiths effect that competes with critical behavior without reaching a QCP [53,54]. By contrast, $\text{Ni}_{1-x}\text{Rh}_x$ is the first member of the $\text{Ni}_{1-y}\text{M}_y$ family where divergent α_V/T and C_{el}/T result in divergent Γ [47], demonstrating the presence of a FM QCP. In fact, for most ferromagnets, when a dilution occurs in the magnetic sublattice, short-range order or spin glass behavior is observed [5]. The only exception is the $5f$ -electron system $\text{Th}_{1-x}\text{U}_x\text{Cu}_2\text{Si}_2$ that the FM transition remains continuous at the critical concentration, where NFL behavior is observed [55].

One plausible scenario to account for the FM QCP in $\text{Ni}_{1-x}\text{Rh}_x$ is the aforementioned BKV theory [6,16,17]. The current study utilized polycrystalline samples and the residual resistivity ratio (not shown), which is often taken as a gauge of the amount of disorder, is small and comparable among the whole series of $\text{Ni}_{1-x}\text{Rh}_x$. To test if the FM quantum criticality in $\text{Ni}_{1-x}\text{Rh}_x$ fulfills the universality class in the strong disorder regime of the BKV theory, the growth of single crystals is imperative and is the subject of an ongoing study. $\text{Ni}_{1-x}\text{Rh}_x$ shows the first occurrence of a FM QCP with dilution of the d -electron

magnetic sublattice. This is in contrast with chemical substitution on the nonmagnetic sublattice in other FM QCP systems [9,10,18–21]. In particular, due to its chemical simplicity, $\text{Ni}_{1-x}\text{Rh}_x$ is an ideal platform for future studies and our work establishes a new approach to explore FM quantum criticality.

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- [1] H. v. Löhneysen, A. Rosch, M. Vojta, and P. Wölfle, Fermi-liquid instabilities at magnetic quantum phase transitions, *Rev. Mod. Phys.* **79**, 1015 (2007).
- [2] E. Schuberth, M. Tippmann, L. Steinke, S. Lausberg, A. Steppke, M. Brando, C. Krellner, C. Geibel, R. Yu, Q. Si, and F. Steglich, Emergence of superconductivity in the canonical heavy-electron metal YbRh_2Si_2 , *Science* **351**, 485 (2016).
- [3] G. R. Stewart, Non-fermi-liquid behavior in d - and f -electron metals, *Rev. Mod. Phys.* **73**, 797 (2001).
- [4] G. R. Stewart, Addendum: Non-fermi-liquid behavior in d - and f -electron metals, *Rev. Mod. Phys.* **78**, 743 (2006).
- [5] M. Brando, D. Belitz, F. M. Grosche, and T. R. Kirkpatrick, Metallic quantum ferromagnets, *Rev. Mod. Phys.* **88**, 025006 (2016).
- [6] D. Belitz, T. R. Kirkpatrick, and Thomas Vojta, First Order Transitions and Multicritical Points in Weak Itinerant Ferromagnets, *Phys. Rev. Lett.* **82**, 4707 (1999).
- [7] S. Ran, C. Eckberg, Q.-P. Ding, Y. Furukawa, T. Metz, S. R. Saha, I.-L. Liu, M. Zic, H. Kim, J. Paglione, and N. P. Butch, Nearly ferromagnetic spin-triplet superconductivity, *Science* **365**, 684 (2019).
- [8] D. A. Sokolov, M. C. Aronson, W. Gannon, and Z. Fisk, Critical Phenomena and the Quantum Critical Point of Ferromagnetic $\text{Zr}_{1-x}\text{Nb}_x\text{Zn}_2$, *Phys. Rev. Lett.* **96**, 116404 (2006).
- [9] S. Jia, P. Jiramongkolchai, M. R. Suchomel, B. H. Toby, J. G. Checkelsky, N. P. Ong, and R. J. Cava, Ferromagnetic quantum critical point induced by dimer-breaking in $\text{SrCo}_2(\text{Ge}_{1-x}\text{P}_x)_2$, *Nat. Phys.* **7**, 207 (2011).
- [10] A. Steppke, R. Küchler, S. Lausberg, E. Lengyel, L. Steinke, R. Borth, T. Lühmann, C. Krellner, M. Nicklas, C. Geibel, F. Steglich, and M. Brando, Ferromagnetic quantum critical point in the heavy-Fermion metal $\text{YbNi}_4(\text{P}_{1-x}\text{As}_x)_2$, *Science* **339**, 933 (2013).
- [11] E. Svanidze, L. Liu, B. Frandsen, B. D. White, T. Besara, T. Goko, T. Medina, T. J. S. Munsie, G. M. Luke, D. Zheng, C. Q. Jin, T. Siegrist, M. B. Maple, Y. J. Uemura, and E. Morosan, Non-Fermi Liquid Behavior Close to a Quantum Critical Point in a Ferromagnetic State Without Local Moments, *Phys. Rev. X* **5**, 011026 (2015).
- [12] N. P. Butch and M. B. Maple, Evolution of Critical Scaling Behavior Near a Ferromagnetic Quantum Phase Transition, *Phys. Rev. Lett.* **103**, 076404 (2009).
- [13] G. Abdul-Jabbar, D. A. Sokolov, C. D. O'Neill, C. Stock, D. Wermeille, F. Demmel, F. Krüger, A. G. Green, F. Lévy-Bertrand, B. Grenier, and A. D. Huxley, Modulated magnetism in PrPtAl , *Nat. Phys.* **11**, 321 (2015).
- [14] V. Taufour, U. S. Kaluarachchi, R. Khasanov, M. C. Nguyen, Z. Guguchia, P. K. Biswas, P. Bonfà, R. De Renzi, X. Lin, S. K. Kim, E. D. Mun, H. Kim, Y. Furukawa, C.-Z. Wang, K.-M. Ho, S. L. Bud'ko, and P. C. Canfield, Ferromagnetic Quantum Critical Point Avoided by the Appearance of Another Magnetic Phase in LaCrGe_3 Under Pressure, *Phys. Rev. Lett.* **117**, 037207 (2016).
- [15] U. S. Kaluarachchi, S. L. Bud'ko, P. C. Canfield, and V. Taufour, Tricritical wings and modulated magnetic phases in LaCrGe_3 under pressure, *Nat. Commun.* **8**, 546 (2017).
- [16] Y. Sang, D. Belitz, and T. R. Kirkpatrick, Disorder Dependence of the Ferromagnetic Quantum Phase Transition, *Phys. Rev. Lett.* **113**, 207201 (2014).
- [17] T. R. Kirkpatrick and D. Belitz, Exponent relations at quantum phase transitions with applications to metallic quantum ferromagnets, *Phys. Rev. B* **91**, 214407 (2015).
- [18] K. Huang, S. Eley, P. F. S. Rosa, L. Civale, E. D. Bauer, R. E. Baumbach, M. B. Maple, and M. Janoschek, Quantum Critical Scaling in the Disordered Itinerant Ferromagnet $\text{UCo}_{1-x}\text{Fe}_x\text{Ge}$, *Phys. Rev. Lett.* **117**, 237202 (2016).
- [19] T. Goko, C. J. Arguello, A. Hamann, T. Wolf, M. Lee, D. Reznik, A. Maisuradze, R. Khasanov, E. Morenzoni, and Y. J. Uemura, Restoration of quantum critical behavior by disorder in pressure-tuned $(\text{Mn,Fe})\text{Si}$, *npj Quantum Mater.* **2**, 44 (2017).
- [20] B. C. Sales, K. Jin, H. Bei, J. Nichols, M. F. Chisholm, A. F. May, N. P. Butch, A. D. Christianson, and M. A. McGuire, Quantum critical behavior in the asymptotic limit of high disorder in the medium entropy alloy $\text{NiCoCr}_{0.8}$, *npj Quantum Mater.* **2**, 33 (2017).
- [21] Y. Lai, S. E. Bone, S. Minasian, M. G. Ferrier, J. Lezama-Pacheco, V. Mocko, A. S. Ditter, S. A. Kozimor, G. T. Seidler, W. L. Nelson, Y.-C. Chiu, K. Huang, W. Potter, D. Graf, T. E. Albrecht-Schmitt, and R. E. Baumbach, Ferromagnetic quantum critical point in CePd_2P_2 with $\text{Pd} \rightarrow \text{Ni}$ substitution, *Phys. Rev. B* **97**, 224406 (2018).
- [22] Y. J. Uemura, T. Goko, I. M. Gat-Malureanu, J. P. Carlo, P. L. Russo, A. T. Savici, A. Aczel, G. J. MacDougall, J. A. Rodriguez, G. M. Luke, S. R. Dunsiger, A. McCollam, J. Arai, Ch. Pfleiderer, P. Böni, K. Yoshimura, E. Baggio-Saitovitch, M. B. Fontes, J. Larrea, Y. V. Sushko, and J. Sereni, Phase separation and suppression of critical dynamics at quantum phase transitions of mnsi and $\text{Sr}_{1-x}\text{Ca}_x\text{RuO}_3$, *Nat. Phys.* **3**, 29 (2007).

- [23] C. L. Huang, D. Fuchs, M. Wissinger, R. Schneider, M. C. Ling, M. S. Scheurer, J. Schmalian, and H. v. Löhneysen, Anomalous quantum criticality in an itinerant ferromagnet, *Nat. Commun.* **6**, 8188 (2015).
- [24] Y. Kraftmakher, Curie point of ferromagnets, *Eur. J. Phys.* **18**, 448 (1997).
- [25] E. Bucher, W. F. Brinkman, J. P. Maita, and H. J. Williams, Magnetic Susceptibility and Specific Heat of Nearly Ferromagnetic NiRh Alloys, *Phys. Rev. Lett.* **18**, 1125 (1967).
- [26] J.-W. Yeh, S.-K. Chen, S.-J. Lin, J.-Y. Gan, T.-S. Chin, T.-T. Shun, C.-H. Tsau, and S.-Y. Chang, Nanostructured high-entropy alloys with multiple principal elements: Novel alloy design concepts and outcomes, *Adv. Eng. Mater.* **6**, 299 (2004).
- [27] See the Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.124.117203> for details of sample preparation, ac magnetic susceptibility, Arrott-Noakes scaling, μ SR, and phonon contributions to the specific heat, which includes Refs. [28–34].
- [28] Kenny Ståhl, https://www.kemi.dtu.dk/english/research/physicalchemistry/protein_og_roentgenkrystallografi/computer_programs.
- [29] F. Hofer, Thermodynamic properties of solid rhodium-nickel alloys, *J. Solid State Chem.* **45**, 303 (1982).
- [30] L. Vegard, Die konstitution der mischkristalle und die raumfüllung der atome, *Z. Phys.* **5**, 17 (1921).
- [31] A. Arrott and J. E. Noakes, Approximate Equation of State for Nickel Near Its Critical Temperature, *Phys. Rev. Lett.* **19**, 786 (1967).
- [32] R. Kubo and T. Toyabe, Magnetic resonance and relaxation, in *Proceedings of the XIVth Colloque Ampere Ljubljana*, edited by R. Blinc (Amsterdam, North-Holland Publ. Co., 1967), p. 810.
- [33] M. L. G. Foy, Neil Heiman, W. J. Kossler, and C. E. Stronach, Precession of Positive Muons in Nickel and Iron, *Phys. Rev. Lett.* **30**, 1064 (1973).
- [34] B. D. Patterson, K. M. Crowe, F. N. Gyax, R. F. Johnson, A. M. Portis, and J. H. Brewer, Precession of μ^+ in single crystal nickel, *Phys. Lett.* **46A**, 453 (1974).
- [35] J. M. Santiago, C.-L. Huang, and E. Morosan, Itinerant magnetic metals, *J. Phys. Condens. Matter* **29**, 373002 (2017).
- [36] D. W. Carnegie and H. Claus, Magnetism and atomic short-range order in Ni-Rh alloys, *Phys. Rev. B* **30**, 407 (1984).
- [37] D. Fuchs, M. Wissinger, J. Schmalian, C.-L. Huang, R. Fromknecht, R. Schneider, and H. v. Löhneysen, Critical scaling analysis of the itinerant ferromagnet $\text{Sr}_{1-x}\text{Ca}_x\text{RuO}_3$, *Phys. Rev. B* **89**, 174405 (2014).
- [38] B. A. Frandsen, L. Liu, S. C. Cheung, Z. Guguchia, R. Khasanov, E. Morenzoni, T. J. S. Munsie, A. M. Hallas, M. N. Wilson, Y. Cai *et al.*, Volume-wise destruction of the antiferromagnetic Mott insulating state through quantum tuning, *Nat. Commun.* **7**, 12519 (2016).
- [39] B. B. Triplett and N. E. Phillips, Low-temperature heat capacity of $\text{Ni}_{0.62}\text{Rh}_{0.38}$, *Phys. Lett.* **37A**, 443 (1971).
- [40] M. Brando, W. J. Duncan, D. Moroni-Klementowicz, C. Albrecht, D. Grüner, R. Ballou, and F. M. Grosche, Logarithmic Fermi-Liquid Breakdown in NbFe_2 , *Phys. Rev. Lett.* **101**, 026401 (2008).
- [41] W. C. Muellner and J. S. Kouvel, Magnetic properties of Ni-Rh alloys near the critical composition for ferromagnetism, *Phys. Rev. B* **11**, 4552 (1975).
- [42] H. Fujiwara, H. Kadomatsu, K. Ohishi, and Y. Yamamoto, Effects of hydrostatic pressure on the Curie temperature of Ni-based alloys (Ni-V, -Cu, -Pd, -Pt and -Rh), *J. Phys. Soc. Jpn.* **40**, 1010 (1976).
- [43] R. Vetter and J. Vuik, Resistivity and curie point of NiRh alloys, *Phys. Status Solidi (A)* **63**, 637 (1981).
- [44] H. P. Wijn, Magnetic Properties of Metals—d-Elements, *Alloys and Compounds* (Springer-Verlag, Berlin Heidelberg, 1991).
- [45] K. Grube, S. Zaum, O. Stockert, Q. Si, and H. v. Löhneysen, Multidimensional entropy landscape of quantum criticality, *Nat. Phys.* **13**, 742 (2017).
- [46] R. Küchler, N. Oeschler, P. Gegenwart, T. Cichorek, K. Neumaier, O. Tegus, C. Geibel, J. A. Mydosh, F. Steglich, L. Zhu, and Q. Si, Divergence of the Grüneisen Ratio at Quantum Critical Points in Heavy Fermion Metals, *Phys. Rev. Lett.* **91**, 066405 (2003).
- [47] L. Zhu, M. Garst, A. Rosch, and Q. Si, Universally Diverging Grüneisen Parameter and the Magnetocaloric Effect Close to Quantum Critical Points, *Phys. Rev. Lett.* **91**, 066404 (2003).
- [48] P. Mohn, *Magnetism in the Solid State: An Introduction* (Springer, Berlin, 2006).
- [49] T. Vojta, Thermal expansion and Grüneisen parameter in quantum Griffiths phases, *Phys. Rev. B* **80**, 041101(R) (2009).
- [50] I. P. Gregory and D. E. Moody, The low temperature specific heat and magnetization of binary alloys of nickel with titanium, vanadium, chromium and manganese, *J. Phys. F* **5**, 36 (1975).
- [51] K. P. Gupta, C. H. Cheng, and P. A. Beck, Low-temperature specific heat of Ni-base fcc solid solutions with Cu, Zn, Al, Si, and Sb, *Phys. Rev.* **133**, A203 (1964).
- [52] M. Nicklas, M. Brando, G. Knebel, F. Mayr, W. Trinkl, and A. Loidl, Non-Fermi-Liquid Behavior at a Ferromagnetic Quantum Critical Point in $\text{Ni}_{1-x}\text{Pd}_x$, *Phys. Rev. Lett.* **82**, 4268 (1999).
- [53] S. Ubaid-Kassis, T. Vojta, and A. Schroeder, Quantum Griffiths Phase in the Weak Itinerant Ferromagnetic Alloy $\text{Ni}_{1-x}\text{V}_x$, *Phys. Rev. Lett.* **104**, 066402 (2010).
- [54] T. Vojta, Quantum Griffiths effects and smeared phase transitions in metals: Theory and experiment, *J. Low Temp. Phys.* **161**, 299 (2010).
- [55] M. Lenkewitz, S. Corsépius, G.-F. v. Blanckenhagen, and G. R. Stewart, Heavy non-fermi-liquid behavior in nearness to ferromagnetism in $\text{Th}_{1-x}\text{U}_x\text{Cu}_2\text{Si}_2$, *Phys. Rev. B* **55**, 6409 (1997).