

Phase diagram of CeRh₂As₂ for out-of-plane magnetic field

P. Khanenko^{1,*}, J. F. Landaeta^{1,2}, S. Ruet¹, T. Lühmann¹, K. Semeniuk¹, M. Pelly³, A. W. Rost³, G. Chajewski⁴,
D. Kaczorowski⁴, C. Geibel¹, S. Khim¹, E. Hassinger², and M. Brando^{1,†}

¹Max Planck Institute for Chemical Physics of Solids, 01187 Dresden, Germany

²Technical University Dresden, Institute for Solid State and Materials Physics, 01062 Dresden, Germany

³Scottish Universities Physics Alliance, School of Physics and Astronomy,
University of St. Andrews, St. Andrews, Fife KY16 9SS, United Kingdom

⁴Institute of Low Temperature and Structure Research, Polish Academy of Sciences, Okólna 2, 50-422 Wrocław, Poland



(Received 22 April 2025; revised 4 July 2025; accepted 9 July 2025; published 8 August 2025)

The heavy-fermion superconductor (SC) CeRh₂As₂ ($T_c = 0.35$ K) shows two SC phases SC1 and SC2 when a magnetic field is applied parallel to the c axis of the tetragonal unit cell. All experiments to date have indicated that the change in SC order parameter detected at $\mu_0 H^* \approx 4$ T is due to strong Rashba spin-orbit coupling at the Ce sites caused by the locally noncentrosymmetric environments of the otherwise globally centrosymmetric crystalline structure. Another phase (phase I) exists in this material below $T_0 = 0.54$ K. In a previous specific heat study [K. Semeniuk *et al.*, *Phys. Rev. B* **107**, L220504 (2023)], we have shown that phase I persists up to a field $\mu_0 H_0 \approx 6$ T, larger than H^* . From thermodynamic arguments, we expected the phase-I boundary line to cross phase SC2 at a tetracritical point. However, we could not find any signature of the phase-I line inside the SC2 phase and speculated that this was because the $T_0(H)$ line is almost perpendicular to the H axis and therefore invisible to T -dependent measurements. This would imply a weak competition between the two order parameters. Here, we report magnetic-field-dependent measurements of the magnetostriction and ac susceptibility on high-quality single crystals. We see clear evidence of the singularity at H_0 inside the SC2 phase and confirm our previous prediction. Furthermore, we observe the transition across the $T^*(H)$ line in T -dependent specific heat measurements, which show that the $T^*(H)$ line is not perpendicular to the field axis but has a positive slope. Our findings support recent muon spin resonance results which suggest coexistence of phase I with SC.

DOI: 10.1103/physrevb.112.L060501

Introduction. Multiphase superconductivity (SC) is very rare. It has been realized in superfluid ³He [1] and only in a few U-based unconventional SCs, i.e., UPt₃ [2–4], thorium-doped UBe₁₃ [5], and UTe₂ [6–8]. Despite many years of experimental and theoretical efforts, there is no model that can fully describe the behavior of these SCs [9].

The recently discovered heavy-fermion (HF) SC in CeRh₂As₂ is the only established non-U-based multiphase unconventional SC to date [10]. Importantly, its behavior can be well described by theories based on strong Rashba spin-orbit coupling at the Ce sites caused by the locally noncentrosymmetric environments of the otherwise globally centrosymmetric crystalline structure [11,12]. Thus, studying CeRh₂As₂ opens a unique opportunity for better

understanding unconventional SC, particularly in locally non-centrosymmetric systems.

The most striking information that connects the SC states in CeRh₂As₂ with the theories mentioned above is the shape of the magnetic H - T phase diagram when a magnetic field is applied parallel to the c axis of the tetragonal unit cell. A refined version of the phase diagram is shown in Fig. 1 and is the main result of our work presented here. The two SC phases SC1 and SC2 are separated by a weak first-order line at $\mu_0 H^* \approx 4$ T. This line was observed in field-dependent magnetization, magnetostriction, and ac-susceptibility measurements [10,13]. In contrast, for an in-plane magnetic field, there is only one SC phase SC1, which is Pauli limited with a critical field of ~ 2 T [10,13,14]. The pronounced anisotropy of the SC phases was also predicted by the same theories [11,12,15–25].

As in the case of the multiphase HF UPt₃ [3], in CeRh₂As₂, there exists another phase, labeled I. This phase is present at temperatures above SC with a transition temperature $T_0 \approx 0.5$ K [14,26] (cf. Fig. 1). Authors of previous studies have suggested that the nature of the ordering is a nonmagnetic quadrupole-density-wave instability supported by the presence of a quartet ground state of the crystal electric field [26–28]. However, nuclear quadrupole resonance/nuclear magnetic resonance [29,30] as well as

*Contact author: pavlo.khanenko@cpfs.mpg.de

†Contact author: manuel.brandt@cpfs.mpg.de

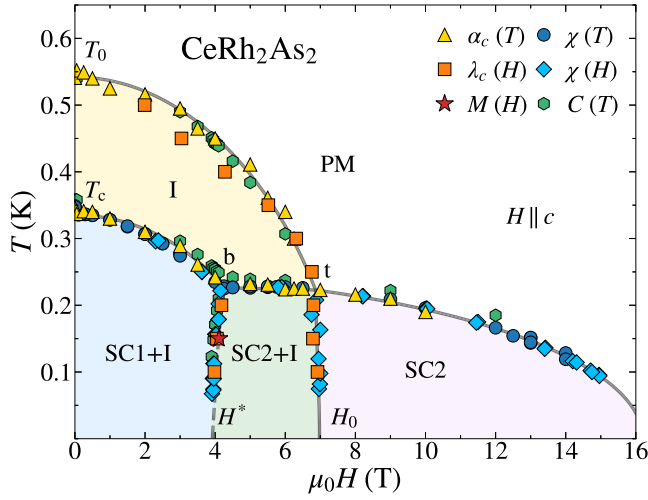


FIG. 1. Refined H - T phase diagram of CeRh_2As_2 for $H \parallel c$ axis. Points are taken from specific heat $C(T)$, magnetic susceptibility $\chi(T, H)$, linear thermal expansion coefficient $\alpha_c(T)$, linear magnetostriction coefficient $\lambda_c(H)$, and magnetization $M(H)$ experiments. The letters b and t indicate the bicritical and tetracritical points discussed in the text. The solid gray lines fit to the GL model described in the text. The dashed gray line is a guide for the eye. Since μSR experiments suggest coexistence of phase I with SC, and the slight change of slope of the $T_0(H)$ line at t implies weak coupling between phase I and SC2, we have labeled the mixed phases SC1 + I and SC2 + I.

recent muon spin resonance (μSR) [31] experiments have clearly detected an antiferromagnetic (AFM) order below T_0 . Also, the presence of AFM quasi-two-dimensional (2D) fluctuations in inelastic neutron scattering experiments [32] and the analysis of the specific heat [33] support the presence of AFM order at T_0 . A possible concomitant ordering of dipolar and quadrupolar degrees of freedom at T_0 is currently under debate and is strongly suggested by the in-plane field phase diagram which shows a substantial increase of T_0 with the field [14,34].

One of the central questions in such systems is the nature of the interplay between the SC state and other ordered states, in the present case phase I. With the present results, we can provide the answer to one essential point, namely, the sign and the strength of the interaction between the SC2 state and phase I. In case of a strong coupling between the order parameters, the symmetry of phase I might reduce the allowed symmetry possibilities for the SC order parameters. In a previous work, Ref. [35], we have shown that the signatures of the phase-I boundary line $T_0(H)$ disappear just before entering the SC2 phase. The highest field at which phase I was clearly detected was $\mu_0 H_0 \approx 5$ T, i.e., a field larger than H^* . From thermodynamic arguments, we predicted that $T_0(H)$ should enter the SC2 phase. However, we could not find any signature of this behavior in our previous T -dependent measurements. We speculated that this was due to the fact that the $T_0(H)$ line is almost perpendicular to the H axis and therefore invisible to T -dependent measurements.

Here, by means of H -dependent magnetostriction and ac-susceptibility measurements on high-quality single crystals,

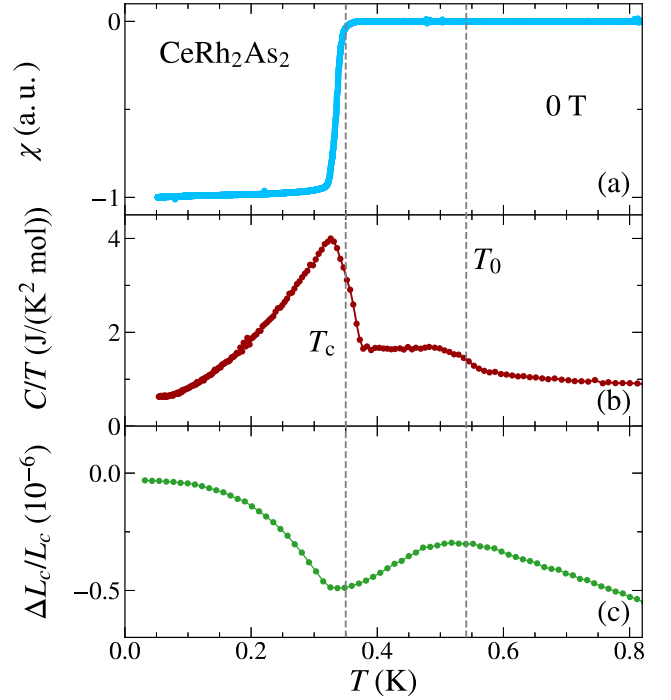


FIG. 2. (a) T dependence of the ac susceptibility $\chi(T)$. The gray dashed vertical lines indicate the position of the transition temperatures T_c and T_0 estimated from the specific heat $C(T)/T$ plotted in (b). (c) T dependence of the linear thermal expansion along the crystallographic c axis $\Delta L(T)_c/L_c$.

we clarify this point and confirm our prediction. The behavior of the phase boundary lines shown in Fig. 1 implies that there is a weak competition between the phase-I and SC2 order parameters. Furthermore, we observe the transition across the $T^*(H)$ line in T -dependent specific heat measurements, which show that this line is not perpendicular to the field axis but has a positive slope. Our refined phase diagram supports coexistence of phase I with SC, as has been also found in recent μSR experiments [31].

Results. The main result of our work is the refined and detailed H - T phase diagram of the best-quality samples of CeRh_2As_2 for $H \parallel c$, which is shown in Fig. 1. The points in the phase diagram were extracted from measurements of the T and H dependence of five thermodynamic quantities. In the following, we show first measurements in zero field and then in magnetic field. We also explain how we extracted the points in Fig. 1 and comment on the nature of the phase transitions according to their signatures. The field H was applied along the [001] direction in all measurements presented here.

The samples used in this study are from the highest-quality batch grown in Bi flux at the Max Planck Institute for Chemical Physics of Solids in Dresden [10]. They were also used for the μSR study in Ref. [31]. These samples have transition temperatures $T_0 = 0.54$ K and $T_c = 0.35$ K (cf. Figs. 1 and 2). In Fig. S1 in the Supplemental Material (SM) [36], we compare the specific heat of three generations of samples with different quality. They are classified in three groups depending on the value of the critical temperatures and the sharpness of the transitions: The better the quality, the higher the critical

temperatures and sharper the signature of the transitions, as expected in HF systems. Group 3 corresponds to the best quality. We also measured ac susceptibility on a sample grown with Bi horizontal-flux method at the Institute of Low Temperature and Structure Research in Wrocław [33,37]. Although this sample has a slightly lower quality, comparable with samples of Group 2 used in Ref. [35], it shows the very same features in field-dependent ac-susceptibility data (cf. Fig. 4).

To quantify the improvements in sample quality between Groups 2 and 3, we performed single-crystal x-ray diffraction on fragments extracted from Group 2 and 3 samples (see section SCXRD in the SM [36]). Notably the Group 2 sample shows clear streaks of secondary reflections centered around the primary ones (Fig. S2 in the SM [36]). The probability distribution of the distance of the secondary reflections from the primary peaks along each principal axis (see Fig. S3 in the SM [36]) is three times broader in the Group 2 crystal than the Group 3 sample in all directions, with the disorder primarily occurring along the c axis. Due to the layered nature of the structure, stacking faults can explain these features. However, our analysis cannot exclude the presence of small ingrowths, with the lattice parameters similar to those of CeRh₂As₂.

Figure 2 shows measurements of the ac susceptibility $\chi(T)$, electronic specific heat coefficient $C(T)/T$, and linear thermal expansion along the crystallographic c axis $\Delta L_c(T)/L_c$ in zero magnetic field. The high quality of the samples is indicated by the same transition temperatures measured in all quantities (cf. Refs. [10,26]) and the sharp anomaly at the SC transition temperature T_c . Both transition temperatures $T_0 = 0.54$ K and $T_c = 0.35$ K were determined by equal entropy construction applied to the specific heat data, as was done in previous works [10,33,35].

Another interesting result is shown in Fig. 3(a): The $T^*(H)$ line, which separates the SC1 from the SC2 phase, is almost perpendicular to the field axis (see Fig. 1). The findings presented here show that the slope of $T^*(H)$ is clearly positive, which is consistent with the analysis of the jumps in the specific heat $\Delta C/T$ measured at the bicritical point (see SM of Ref. [10]). In the T -dependent specific heat measurement at exactly 4.05 T, we indeed detect the phase transition from SC1 + I to SC2 + I at ~ 0.18 K [red arrow in Fig. 3(a)], indicating a small entropy change. The same feature rapidly shifts to lower temperatures when decreasing the field marginally from 4.05 to 3.95 T. The transition points are plotted in Fig. 1 as green hexagons. The tiny dT^*/dH slope observed in our experiments is predicted by theory [10,11], but it could also be a signature of the recently proposed SC meron state [38], which is a state in which the SC electron spins assume a skyrmion-lattice-like structure.

In Ref. [33], additional features were observed slightly below $T_c(H)$, sharp first-order peaks, which could be related to a vortex-lattice melting transition [39]. Despite the high quality of our samples, we could not see these sharp first-order phase transitions, likely because of the semiadiabatic method used here [40].

Both phase transitions at T_c and T_0 and their field dependence could be detected as kinks or maxima in $\Delta L(T)_c/L_c$ (marked by green and orange arrows in Fig. 3(b), see also Fig. S4 in the SM [36]). These signatures indicate that both transitions remain second order also in the magnetic field. The

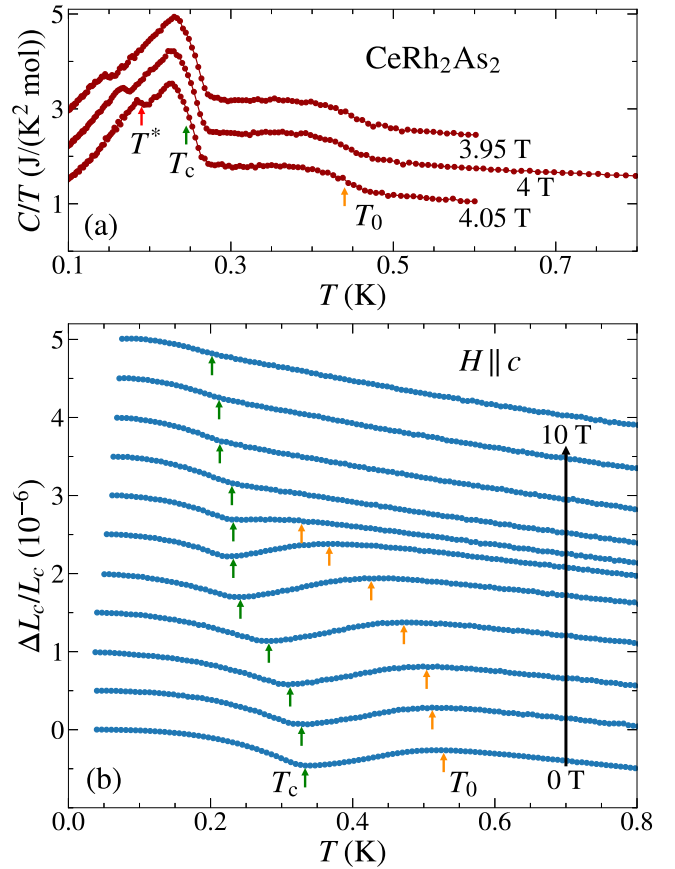


FIG. 3. (a) Electronic specific heat coefficient $C(T)/T$ measured at 3.95, 4, and 4.05 T, i.e., the fields near which the $T^*(H)$ line is observed (cf. Fig. 1). The transition across this line from SC1 to SC2 is indicated by the red arrow at T^* . (b) Linear thermal expansion $\Delta L(T)_c/L_c$ measured at constant magnetic fields in steps of 1 T from 0 to 10 T. The curves are shifted upward by 0.5×10^{-6} for clarity. The green and orange arrows indicate T_c and T_0 , respectively.

associated transition temperatures, extracted from the thermal expansion coefficient $\alpha_c = \frac{1}{L_c} \frac{d(\Delta L_c)}{dT}$, are plotted in Fig. 1 as yellow triangles.

The most relevant measurements are shown in Fig. 4. These are H -dependent scans at constant temperatures of the ac susceptibility $\chi(H)$ and linear magnetostriction $\Delta L_c(H)/L_c$. The associated transition fields, extracted from the magnetostriction coefficient $\lambda_c = \frac{1}{L_c} \frac{d(\Delta L_c)}{dH}$, are plotted in Fig. 1 as orange squares. All measurements were carried out with up and down sweeps. Nevertheless, we could not observe any relevant hysteresis at any of the transition fields, i.e., only tiny hysteresis of the order of 10 mT comparable with the remanent field of our SC magnets. A magnified view of the transitions at H_0 and H^* in the susceptibility is shown in Fig. S5 in the SM [36]. This implies that all transitions are either second or weakly first order. We have marked all corresponding features in the data by arrows: Green arrows indicate the upper critical field of the SC2 phase, which we estimate to be when we recover 90% of the normal state in the diamagnetic signal, and red arrows mark the transition fields H^* between the SC1 + I and SC2 + I phases. For $T \leq 0.22$ K, the signatures of the transition at H^* are kinks in

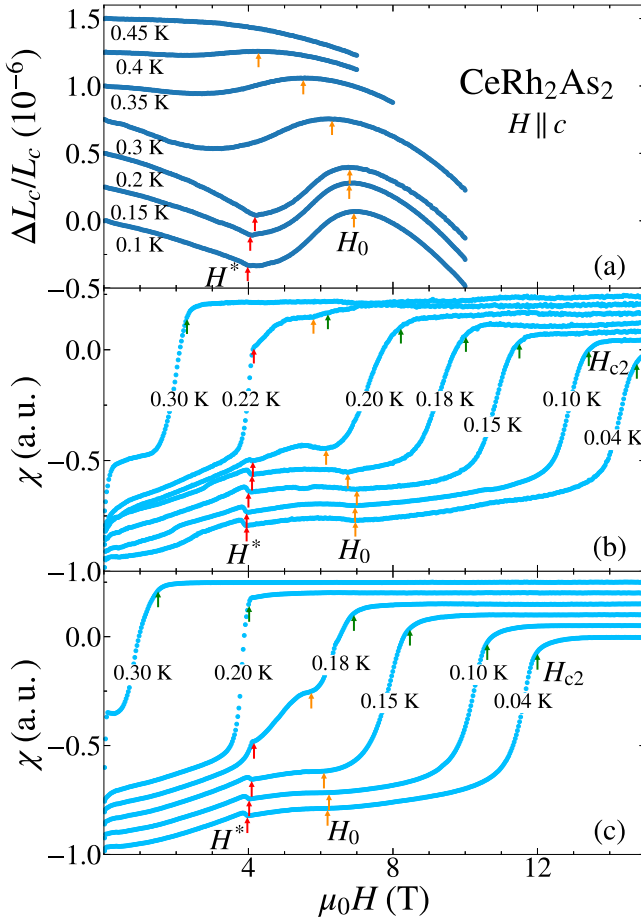


FIG. 4. Field dependence of the (a) linear magnetostriction along the crystallographic c axis $\Delta L_c(H)/L_c$ and of the (b) and (c) ac susceptibility $\chi(H)$ measured at different constant temperatures. In (a), the sample temperature is shown, whereas in (b) and (c), the mixing chamber temperature is shown: The critical temperatures used in Fig. 1 were determined from the simultaneously recorded sample temperatures. Panel (b) shows measurements on the best quality sample (Group 3), whereas panel (c) shows measurements on a slightly worse sample (Group 2) for comparison. We do plot here only up-sweep data since we could not see relevant hysteresis between sweeps up and down. The red and orange arrows indicate H^* and H_0 , respectively. The SC upper critical field H_{c2} is indicated by green arrows. Curves in all panels are shifted for clarity.

$\Delta L_c(H)/L_c$ and steplike features in $\chi(H)$, which correspond to the kinks observed in magnetization in Fig. 5 (red arrows). This behavior points to a second-order or weakly first-order phase transition. Moreover, H^* effectively does not vary with sample quality [cf. Figs. 4(b) and 4(c)]. Robustness of the SC1-SC2 transition against disorder (see Fig. S6 in the SM [36]) is expected for theories based on strong Rashba spin-orbit coupling if the ratio of Rashba and interlayer coupling does not change. Finally, the orange arrows indicate the critical field H_0 of phase I, which can also be found inside the phase SC2. The signatures here are minima in $\chi(H)$ (see Fig. S5 in the SM [36]) and maxima in $\Delta L_c(H)/L_c$. In this case, there is a difference in the values of H_0 between the data on the best-quality samples and those on the less pure sample, because H_0 is proportional to T_0 and therefore higher

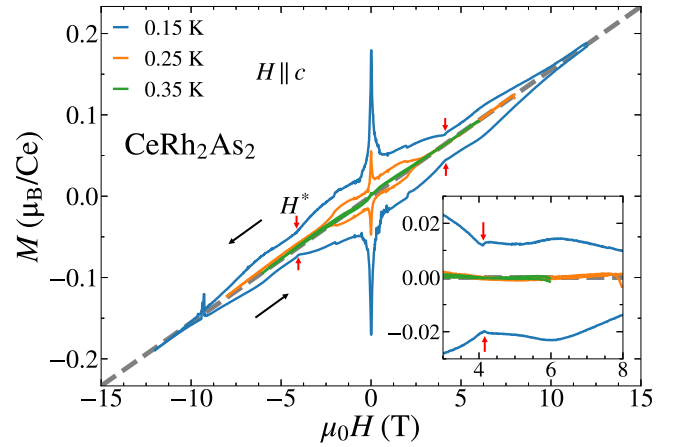


FIG. 5. Field dependence of the magnetization $M(H)$ taken at three different temperatures. The hysteresis is due to vortex pinning and disappears above the SC transition temperature (cf. green curve). The red arrows mark the critical field H^* , while at H_0 , we observe broad maxima. The steplike features at ± 2 T are artifacts due to the change in ramp rate of the magnet which influences the temperature controller.

in the best-quality sample. It is worth noting that, without T -dependent thermodynamic measurements and spectroscopic evidence for an ordered state in phase I [31], the signatures at $H_0(T)$ could be interpreted as a crossover rather than a phase transition.

Another interesting observation is that, in the non-SC state, the ac susceptibility does not detect a signature at either T_0 or H_0 . The reason is probably that the AFM ordered moments are very small ($\leq 0.1 \mu_B$) and mainly located within the basal plane [34,41,42], whereas our measurements were carried out with ac field along the c axis. At the same time, the likely reason we see the signature within the SC state is an indirect one: Phase I presumably induces a small gap or a reconstruction of the Fermi surface that affects the screening currents of the SC state, which we see as an anomaly in the susceptibility.

The final phase diagram of CeRh_2As_2 for $H \parallel c$, shown in Fig. 1, was constructed by using all features observed in our measurements and all information from other experiments. In Ref. [35], we used a Ginzburg-Landau theory of coupled order parameters [43,44] to analyze the interplay between the SC order parameter Δ and the phase-I order parameter $\mathbf{Q}$ with a coupling term $\lambda \Delta^2 \mathbf{Q}^2$, where λ indicates the strength of the coupling as well as its nature, $\lambda > 0$ for competing and $\lambda < 0$ for supporting coupling. The model is well described in the SM of Ref. [35]. We applied this theory to the phase boundaries intersecting at the tetracritical point t (see Fig. 1). We were able to reproduce the observed phase boundaries for SC2 and I and their slope change in the vicinity of t . The fits are shown as solid gray lines in Fig. 1. With the addition of the recently discovered section of $T_0(H)$ line, the value of λ is now shown to be between 20 and 50% of that necessary to induce a first-order phase transition, i.e., the coupling is weakly competitive. As predicted in Refs. [35,45], $T_0(H)$ changes slope slightly when entering the SC2 phase and is almost vertical inside the SC2 phase. The weak coupling is corroborated by the μSR experiments [31], in which evidence of

microscopic coexistence between the SC phases and phase I was found.

Conclusions. We have presented a refined and complete version of the phase diagram of the HF SC CeRh₂As₂ for a magnetic field parallel to the tetragonal c axis. We have found signatures of the phase-I boundary line $T_0(H)$ within the SC phase SC2, confirming our presumption that there is a weak competing coupling between the order parameters of phase I and SC2. Our results corroborate recent μ SR results which suggest microscopic coexistence of phase I with SC. Moreover, we find evidence of the putative first-order $T^*(H)$ transition line in T -dependent specific heat measurements. We could not detect relevant hysteresis in all H -dependent measurements across this line. This suggests that $T^*(H)$ transition is either second or weakly first order.

Acknowledgments. We are indebted to T. Lorenz, M. Garst, F. Jakubczyk, and C. Timm for useful discussions. This

work is also supported by the joint Agence National de la Recherche and Deutsche Forschungsgemeinschaft (DFG) program Fermi-NES through Grant No. GE602/4-1 (C.G. and E.H.). Additionally, E.H. acknowledges funding by the DFG through CRC1143 (Project No. 247310070) and the Würzburg-Dresden Cluster of Excellence on Complexity and Topology in Quantum Matter—ct.qmat (EXC 2147, Project ID 390858490). This work is supported by the ERC grant (Ixtreme, GA 101125759). S.K. was supported by the Max Planck Society and the DFG—KH 387/1-1. A.R. and M.P. were supported by the Engineering and Physical Sciences Research Council (Grants No. EP/P024564/1, No. EP/V049410/1, and No. EP/L015110/1). M.P. acknowledges financial support by the International Max Planck Research School for Chemistry and Physics of Quantum Materials.

Data availability. The data that support the findings of this article are openly available [46].

- [1] A. J. Leggett, A theoretical description of the new phases of liquid ³He, *Rev. Mod. Phys.* **47**, 331 (1975).
- [2] R. A. Fisher, S. Kim, B. F. Woodfield, N. E. Phillips, L. Taillefer, K. Hasselbach, J. Flouquet, A. L. Giorgi, and J. L. Smith, Specific heat of UPt₃: Evidence for unconventional superconductivity, *Phys. Rev. Lett.* **62**, 1411 (1989).
- [3] G. Bruls, D. Weber, B. Wolf, P. Thalmeier, B. Lüthi, A. de Visser, and A. Menovsky, Strain–order-parameter coupling and phase diagrams in superconducting UPt₃, *Phys. Rev. Lett.* **65**, 2294 (1990).
- [4] S. Adenwalla, S. W. Lin, Q. Z. Ran, Z. Zhao, J. B. Ketterson, J. A. Sauls, L. Taillefer, D. G. Hinks, M. Levy, and B. K. Sarma, Phase diagram of UPt₃ from ultrasonic velocity measurements, *Phys. Rev. Lett.* **65**, 2298 (1990).
- [5] H. R. Ott, H. Rudigier, Z. Fisk, and J. L. Smith, Phase transition in the superconducting state of U_{1-x}Th_xBe₁₃ ($x = 0$ –0.06), *Phys. Rev. B* **31**, 1651 (1985).
- [6] 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).
- [7] D. Braithwaite, M. Vališka, G. Knebel, G. Lapertot, J. P. Brison, A. Pourret, M. E. Zhitomirsky, J. Flouquet, F. Honda, and D. Aoki, Multiple superconducting phases in a nearly ferromagnetic system, *Commun. Phys.* **2**, 147 (2019).
- [8] D. Aoki, F. Honda, G. Knebel, D. Braithwaite, A. Nakamura, D. Li, Y. Homma, Y. Shimizu, Y. J. Sato, J.-P. Brison *et al.*, Multiple superconducting phases and unusual enhancement of the upper critical field in UTe₂, *J. Phys. Soc. Jpn.* **89**, 053705 (2020).
- [9] L. Taillefer, Scattering and pairing in cuprate superconductors, *Annu. Rev. Condens. Matter Phys.* **1**, 51 (2010).
- [10] S. Khim, J. F. Landaeta, J. Banda, N. Bannor, M. Brando, P. M. R. Brydon, D. Hafner, R. Kuchler, R. Cardoso-Gil, U. Stockert *et al.*, Field-induced transition within the superconducting state of CeRh₂As₂, *Science* **373**, 1012 (2021).
- [11] T. Yoshida, M. Sigrist, and Y. Yanase, Pair-density wave states through spin-orbit coupling in multilayer superconductors, *Phys. Rev. B* **86**, 134514 (2012).
- [12] M. Sigrist, D. F. Agterberg, M. H. Fischer, J. Goryo, F. Loder, S.-H. Rhim, D. Maruyama, Y. Yanase, T. Yoshida, and S. J. Youn, Superconductors with staggered non-centrosymmetry, *J. Phys. Soc. Jpn.* **83**, 061014 (2014).
- [13] J. F. Landaeta, P. Khanenko, D. C. Cavanagh, C. Geibel, S. Khim, S. Mishra, I. Sheikin, P. M. R. Brydon, D. F. Agterberg, M. Brando *et al.*, Field-angle dependence reveals odd-parity superconductivity in CeRh₂As₂, *Phys. Rev. X* **12**, 031001 (2022).
- [14] P. Khanenko, D. Hafner, K. Semeniuk, J. Banda, T. Lühmann, F. Bärthel, T. Kotte, J. Wosnitzer, G. Zwirgagl, C. Geibel *et al.*, Origin of the non-Fermi-liquid behavior in CeRh₂As₂, *Phys. Rev. B* **111**, 045162 (2025).
- [15] D. Möckli, Y. Yanase, and M. Sigrist, Orbitally limited pair-density-wave phase of multilayer superconductors, *Phys. Rev. B* **97**, 144508 (2018).
- [16] E. G. Schertenleib, M. H. Fischer, and M. Sigrist, Unusual H - T phase diagram of CeRh₂As₂: The role of staggered noncentrosymmetry, *Phys. Rev. Res.* **3**, 023179 (2021).
- [17] A. Skurativska, M. Sigrist, and M. H. Fischer, Spin response and topology of a staggered-Rashba superconductor, *Phys. Rev. Res.* **3**, 033133 (2021).
- [18] K. Nogaki, A. Daido, J. Ishizuka, and Y. Yanase, Topological crystalline superconductivity in locally noncentrosymmetric CeRh₂As₂, *Phys. Rev. Res.* **3**, L032071 (2021).
- [19] A. Ptok, K. J. Kapcia, P. T. Jochym, J. Łażewski, A. M. Oleś, and P. Piekarczyk, Electronic and dynamical properties of CeRh₂As₂: Role of Rh₂As₂ layers and expected orbital order, *Phys. Rev. B* **104**, L041109 (2021).
- [20] D. Möckli and A. Ramires, Two scenarios for superconductivity in CeRh₂As₂, *Phys. Rev. Res.* **3**, 023204 (2021).
- [21] D. C. Cavanagh, T. Shishidou, M. Weinert, P. M. R. Brydon, and D. F. Agterberg, Nonsymmorphic symmetry and field-driven odd-parity pairing in CeRh₂As₂, *Phys. Rev. B* **105**, L020505 (2022).
- [22] K. Nogaki and Y. Yanase, Even-odd parity transition in strongly correlated locally noncentrosymmetric superconductors: Application to CeRh₂As₂, *Phys. Rev. B* **106**, L100504 (2022).
- [23] J. Ishizuka, K. Nogaki, M. Sigrist, and Y. Yanase, Correlation-induced Fermi surface evolution and topological crystalline

- superconductivity in CeRh_2As_2 , *Phys. Rev. B* **110**, L140505 (2024).
- [24] B. K. Nally and P. M. R. Brydon, Phase diagram of strongly-coupled Rashba systems, *New J. Phys.* **26**, 093015 (2024).
- [25] C. Lee, D. F. Agterberg, and P. M. R. Brydon, Unified picture of superconductivity and magnetism in CeRh_2As_2 , *Phys. Rev. Lett.* **135**, 026003 (2025).
- [26] D. Hafner, P. Khanenko, E.-O. Eljaouhari, R. K  chler, J. Banda, N. Bannor, T. L  hmann, J. F. Landaeta, S. Mishra, I. Sheikin *et al.*, Possible quadrupole density wave in the superconducting Kondo lattice CeRh_2As_2 , *Phys. Rev. X* **12**, 011023 (2022).
- [27] D. S. Christovam, M. Ferreira-Carvalho, A. Marino, M. Sundermann, D. Takegami, A. Melendez-Sans, K. D. Tsuei, Z. Hu, S. R   ler, M. Valvidares *et al.*, Spectroscopic evidence of Kondo-induced quasiquartet in CeRh_2As_2 , *Phys. Rev. Lett.* **132**, 046401 (2024).
- [28] T. Takimoto and P. Thalmeier, Theory of induced quadrupolar order in tetragonal YbRu_2Ge_2 , *Phys. Rev. B* **77**, 045105 (2008).
- [29] M. Kibune, S. Kitagawa, K. Kinjo, S. Ogata, M. Manago, T. Taniguchi, K. Ishida, M. Brando, E. Hassinger, H. Rosner *et al.*, Observation of antiferromagnetic order as odd-parity multipoles inside the superconducting phase in CeRh_2As_2 , *Phys. Rev. Lett.* **128**, 057002 (2022).
- [30] S. Ogata, S. Kitagawa, K. Kinjo, K. Ishida, M. Brando, E. Hassinger, C. Geibel, and S. Khim, Parity transition of spin-singlet superconductivity using sublattice degrees of freedom, *Phys. Rev. Lett.* **130**, 166001 (2023).
- [31] S. Khim, O. Stockert, M. Brando, C. Geibel, C. Baines, T. J. Hicken, H. Luetkens, D. Das, T. Shiroka, Z. Guguchia *et al.*, Coexistence of local magnetism and superconductivity in the heavy-fermion compound CeRh_2As_2 revealed by μSR studies, *Phys. Rev. B* **111**, 115134 (2025).
- [32] T. Chen, H. Siddiquee, Q. Xu, Z. Rehfuss, S. Gao, C. Lygouras, J. Drouin, V. Morano, K. E. Avers, C. J. Schmitt *et al.*, Quasi-two-dimensional antiferromagnetic spin fluctuations in the spin-triplet superconductor candidate CeRh_2As_2 , *Phys. Rev. Lett.* **133**, 266505 (2024).
- [33] G. Chajewski and D. Kaczorowski, Discovery of magnetic phase transitions in heavy-fermion superconductor CeRh_2As_2 , *Phys. Rev. Lett.* **132**, 076504 (2024).
- [34] B. Schmidt and P. Thalmeier, Anisotropic magnetic and quadrupolar H - T phase diagram of CeRh_2As_2 , *Phys. Rev. B* **110**, 075154 (2024).
- [35] K. Semeniuk, D. Hafner, P. Khanenko, T. L  hmann, J. Banda, J. F. Landaeta, C. Geibel, S. Khim, E. Hassinger, and M. Brando, Decoupling multiphase superconductivity from normal state ordering in CeRh_2As_2 , *Phys. Rev. B* **107**, L220504 (2023).
- [36] See Supplemental Material at <https://link.aps.org/supplemental/10.1103/gt54-tvc2> for a comparison of the specific heat capacity of samples of various quality, single-crystal x-ray diffraction information, a full set of the thermal expansion data, a magnified view of the transitions at H_0 and H^* , and SC phase diagrams of samples of various quality
- [37] G. Chajewski, D. Szyma  ski, M. Daszkiewicz, and D. Kaczorowski, Horizontal flux growth as an efficient preparation method of CeRh_2As_2 single crystals, *Mater. Horiz.* **11**, 855 (2024).
- [38] A. Minamide and Y. Yanase, Superconducting meron phase in locally noncentrosymmetric superconductors, *Phys. Rev. Lett.* **134**, 026002 (2025).
- [39] A. Schilling, R. A. Fisher, N. E. Phillips, U. Welp, W. K. Kwok, and G. W. Crabtree, Anisotropic latent heat of vortex-lattice melting in untwinned $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, *Phys. Rev. Lett.* **78**, 4833 (1997).
- [40] H. Wilhelm, T. L  hmann, T. Rus, and F. Steglich, A compensated heat-pulse calorimeter for low temperatures, *Rev. Sci. Instrum.* **75**, 2700 (2004).
- [41] S. Ogata, S. Kitagawa, K. Kinjo, K. Ishida, M. Brando, E. Hassinger, C. Geibel, and S. Khim, Appearance of c -axis magnetic moment in odd-parity antiferromagnetic state in CeRh_2As_2 revealed by ^{75}As -NMR, *Phys. Rev. B* **110**, 214509 (2024).
- [42] J. Juraszek, G. Chajewski, D. Kaczorowski, M. Konczykowski, D. F. Agterberg, and T. Cichorek, Nodeless superconducting state in the presence of zero-field staggered magnetization in CeRh_2As_2 , [arXiv:2502.14423](https://arxiv.org/abs/2502.14423).
- [43] Y. Imry, On the statistical mechanics of coupled order parameters, *J. Phys. C* **8**, 567 (1975).
- [44] R. M. Fernandes and J. Schmalian, Competing order and nature of the pairing state in the iron pnictides, *Phys. Rev. B* **82**, 014521 (2010).
- [45] F. Jakubczyk, J. M. Link, and C. Timm, Composite superconducting orders and magnetism in CeRh_2As_2 , [arXiv:2506.08097](https://arxiv.org/abs/2506.08097).
- [46] P. Khanenko, J. F. Landaeta, S. Ruet, T. L  hmann, K. Semeniuk, M. Pelly, A. W. Rost, G. Chajewski, D. Kaczorowski, C. Geibel *et al.*, Data for ‘‘The phase diagram of CeRh_2As_2 for out-of-plane magnetic field’’, *Phys. Rev. B Letter* (2025), <https://doi.org/10.17617/3.HMLCQN>, Edmond, V1.