INTRODUCTION

Although quantum mechanics was developed to treat nonrelativistic interacting particles, it has also been widely used to describe collective phenomena in condensed matter physics. A macroscopic quantity of interacting particles (~10²³) can give rise to novel quantum phases with emergent magnetic and transport properties that are currently hotly debated among theorists and experimentalists alike. Particularly exciting are quantum liquids, including superconducting condensates, that feature coherence phenomena over macroscopic length scales. Pressure, magnetic field, or chemical substitution can induce quantum phase transitions that originate from fluctuations that are governed by Heisenberg’s uncertainty principle. These collective quantum fluctuations can trigger the collapse or emergence of an order parameter, and they can even dominate the finite temperature properties. Quantum fluctuations generally separate phases with different organizing principles (1, 2), leading to magnetic phases with different symmetry as the strength of the fluctuations evolve. This has been demonstrated, for instance, by quantum magnetic insulators (3).

Strong electronic correlations and quantum fluctuations are thought to be at the origin of unconventional superconductivity in many materials. Examples include the layered copper oxides (4), the iron-based pnictides, and the heavy-fermion (HF) superconductors (5). CeCoIn₅ is an exceptional material because it features spin-density wave (SDW) order that emerges from the superconducting condensate (6). The material is an ultraclean, ambient-pressure, dₓ²−ᵧ² superconductor (Tₓ = 2.3 K) (7) that displays a quasi-two-dimensional Fermi surface (8, 9). Superconductivity is Pauli-limited (10) and coexists at high fields with a SDW that emerges with an ordered moment μ(11 T) = 0.15(5)μ₀ (6, 11–14). Magnetism exists only inside the superconducting state and collapses in a first-order transition at the superconducting upper critical field. The ordering wave vector, Q = (0.45, 0.45, 0.5), is pinned along the nodes of the superconducting gap (11) and may result from the condensation of superconducting quasi-particle excitations with increasing magnetic field (15, 16). All this provides evidence for a coupling between superconductivity and magnetic order (11, 12). However, the microscopic interpretation and the nature of the order parameters of this so-called Q phase are still debated (6, 15–23).

The Q phase is highly sensitive upon doping and has been suppressed in all previously reported cases (24–27). However, recent studies on Nd₀.₀₅Ce₀.₉₅CoIn₅ (28, 29) revealed SDW magnetic order with a similar ordering wave vector as the Q phase for T < Tₛ = 0.8 K at zero field (29). The family of Nd-substituted CeCoIn₅, Nd₁₋ₓCeₓCoIn₅, displays a rich phase diagram featuring a HF ground state (x > 0.5), superconductivity (x > 0.78), and magnetism (x < 1) (28). The substitution of Nd for Ce in CeCoIn₅ introduces localized moments, reduces the hybridization of 4f-bands with the Fermi surface, and weakens the coherence of these heavy bands. This causes the destruction of itinerant magnetism and the emergence of localized moment magnetism at x < 0.5. Small Nd concentrations gradually weaken the superconducting pairing strength, as observed in the reduction in the specific-heat jump (28). The implantation of a small amount of Nd impurities in CeCoIn₅ has a similar effect on superconductivity as the substitution with Kondo holes (29) and acts predominantly as random disorder (see the Supplementary Materials). However, the nature of the magnetic order for small Nd substitutions, such as in Nd₀.₀₅Ce₀.₉₅CoIn₅, and its relationship to the SDW in the Q phase is currently not understood.

RESULTS

Evidence for two distinct magnetic phases inside the superconducting condensate

We studied the magnetic order in Nd₀.₀₅Ce₀.₉₅CoIn₅ as a function of field for H || [1 1 0]. Figure 1 shows neutron diffraction data at several magnetic fields and T = 40 mK along the (q, q, 0.5) reciprocal wave vector given in reciprocal lattice units. A well-defined magnetic Bragg peak is observed at zero field, consistent with previous measurements (29). With increasing field, the peak first increases in intensity but then completely vanishes around μ₀H* = 8 T (Fig. 1D). The key observation is that the peak reappears at higher fields, as shown in Fig. 1 (E and F). The magnetic Bragg peaks were fitted with a Gaussian line shape, showing that the width of the Bragg peaks is resolution-limited at all fields. The peak intensity, Iₚ, is shown in Fig. 2 as a function of field and provides direct evidence for two distinct magnetic phases: a low-field...
phase (SDW phase) for $\mu_0 H < 8$ T and a high-field phase for $8 < \mu_0 H < 11$ T, which we call Q phase because it shares many properties with the Q phase of CeCoIn$_5$. The Q phase in Nd$_{0.05}$Ce$_{0.95}$CoIn$_5$ appears for fields larger than 8 T, and its magnetic Bragg peak increases in intensity with increasing field. At $\mu_0 H = 11.0(2)$ T, it collapses in a sharp transition together with superconductivity. This shows that magnetic order is coupled to superconductivity at high fields—similar to the Q phase in undoped CeCoIn$_5$.

The HT phase diagram of the magnetic phases in Nd$_{0.05}$Ce$_{0.95}$CoIn$_5$ is shown in Fig. 3 and shows additional similarities of the high-field phases in pure and doped CeCoIn$_5$: The Q phase in both compounds features very similar HT phase boundaries, and magnetic order is suppressed with increasing temperature. In a further similarity, the field-induced transition from the Q phase to the normal state in Nd$_{0.05}$Ce$_{0.95}$CoIn$_5$ remains first-order at $H_{c2}(T)$ for $T < 300$ mK. Our results clearly establish that the Q phase in CeCoIn$_5$ is stable under 5% Nd doping of the Ce site.

Field-induced magnetic instability separates two SDWs with identical symmetry
As shown in Fig. 1D, a diffuse signal replaces the magnetic Bragg peak around $\mu_0 H^* \approx 8$ T. This demonstrates that there is a magnetic instability around $H^*$ where magnetic order is absent and separates the SDW phase and the Q phase. Such diffuse scattering typically arises from short-range static or dynamic magnetic correlations. The field dependence of the magnetic Bragg peak intensity is linear as a function of field in the proximity of $H^*$, as shown in Fig. 2. Because the magnetic neutron intensity is proportional to the square of the magnetic moment, this means that the ordered magnetic moment $M$ behaves as $M = M_0|H/H^* - 1|^\beta$, where $\beta = 0.5$ and $M_0 = 0.19(1)\mu_B$ for $H < H^*$ and $M_0 = 0.28(2)\mu_B$ for $H > H^*$, respectively with $\mu_0 H^* = 8.0(2)$ T. A mean-field exponent $\beta = 0.5$ is also observed over a large field range as in the Q phase of the undoped compound (6) and is expected for quantum phase transitions (30). Although we do not have direct evidence of quantum fluctuations, we point out that the HT phase diagram suggests the presence of a quantum critical region around $H^*$ that expands with increasing temperature.

![Fig. 1. Magnetic order at various magnetic fields.](image1)

![Fig. 2. Discovery of a magnetic instability inside the superconducting phase.](image2)
The field dependence of the in-plane component of the wave vector transfer, $q$, is shown in Fig. 4. The data display a linear decrease in the wave number from $q \approx 0.448$ at zero field to $q \approx 0.441$ at 10.5 T and appear to be unaffected by the disappearance of magnetic order around $\mu_0 H^* \approx 8$ T, which is probably related to robust features of the Fermi surface topology. The weak field dependence of the wave vector transfer is in contrast to the Q phase in CeCoIn$_5$, where the wave vector is independent of the magnetic field (11, 12). The symmetry of the magnetic order is identical for the low-field SDW phase and high-field Q phase: At both zero field and $\mu_0 H = 10.5$ T, an identical amplitude-modulated SDW with field-dependent magnetic moments aligned along the $c$ axis (see Fig. 4, inset) and magnetic moments of $\mu(0 \text{ T}) = 0.10(5) \mu_B$ and $\mu(10.5 \text{ T}) = 0.15(5) \mu_B$ are found, respectively. For increasing fields, the magnetic peak intensity increases and reaches a broad maximum at $\mu_0 H \approx 4$ T before it gradually weakens toward $H^*$. At $\mu_0 H = 4$ T, the magnetic structure is also an amplitude-modulated SDW with a somewhat larger magnetic moment. This initial increase of intensity may result from a nonuniform magnetic domain population under a magnetic field. However, the magnetic structure determination clearly demonstrates that the symmetry of the magnetic structure does not change within the SDW phase.

**DISCUSSION**

The identical magnetic symmetry of the ground states in the SDW phase and the Q phase demonstrates that the magnetic instability at $\mu_0 H^* = 8$ T is not purely driven by magnetic fluctuations and that it must emerge from other types of fluctuations. Because the Kondo breakdown in Nd$_{0.95}$Ce$_{0.05}$CoIn$_5$ occurs around $x = 0.5$ (28), we exclude the possibility that the observed magnetic instability for $x = 0.95$ is driven by charge valence fluctuations. On the other hand, it is well known that Pauli-limited superconductors feature instabilities toward complex superconducting phases at high fields, including modulated superconductivity and phases of coexisting magnetic and superconducting order (20, 31, 32). Our results may be explained by a modification of the superconducting condensate that induces a change in the magnetic properties. This is consistent with a recently proposed scenario in undoped CeCoIn$_5$, where SDW order only exists for fields higher than $\mu_0 H = 9.8$ T and is induced by the emergence of $p$-wave superconductivity in the $d$-wave condensate (6, 12, 33, 34). The scenario of novel superconductivity for high fields in the tetragonal plane of CeCoIn$_5$ is expected from a number of microscopic theories (16–22).

We note that the HT phase diagram of Nd$_{0.05}$Ce$_{0.95}$CoIn$_5$ shows some qualitative similarities with the $xT$ phase diagram of La-based cuprate La$_{2-x}$Ba$_x$CuO$_4$, where two superconducting phases exist in the presence of charge and stripe order and are separated by one or more critical points (35). For Nd$_{0.05}$Ce$_{0.95}$CoIn$_5$, it needs to be determined whether the magnetic instability is caused by a single or several quantum phase transitions. In this respect, it will be important to study the HT phase diagrams of Nd$_{1-x}$Ce$_x$CoIn$_3$ for $x > 0.95$.

In summary, we report the discovery of a magnetic instability region inside the superconducting phase of Nd$_{0.05}$Ce$_{0.95}$CoIn$_3$ that separates two antiferromagnetic phases with identical symmetry. Whereas a low-field SDW is suppressed at $\mu_0 H^* = 8$ T, another SDW emerges from fields $\mu_0 H^* > 8$ T and shares many properties with the Q phase of CeCoIn$_5$, such as the sudden collapse of the SDW at the upper critical field. Our experiment shows that the Q phase in CeCoIn$_5$ is stable under 5% Nd doping of the Ce site. The identical magnetic symmetry of the two magnetically ordered phases suggests a quantum phase transition driven by a modification of the superconducting condensate.

**MATERIAL AND METHODS**

Neutron diffraction measurements were carried out on the thermal-neutron lifting-counter two-axis spectrometer D23, the single-crystal four-circle diffractometer D10, and the cold-neutron three-axis spectrometer.
IN12 at the Institut Laue-Langevin (Grenoble, France), and the cold-neutron triple-axis spectrometer RITA-II at the Swiss Spallation Neutron Source SINQ, Paul Scherrer Institut (Villigen, Switzerland). For all measurements, the same single crystal of mass $m = 64$ mg was used (see also the Supplementary Materials). The experiments required temperatures down to $T = 40$ mK and maximal fields of $\mu_0 H = 12$ T, which were achieved using vertical-field magnets with dilution inserts. On D23, an incident neutron wavelength $\lambda = 1.28$ Å was used. The experiment on D10 was conducted with a neutron wavelength $\lambda = 2.36$ Å. For the experiment, we used the $^3$He single detector in a four-circle setup and optimized the signal-to-noise ratio via the analyzer option of the instrument. A clean wavelength $\lambda = 4.83$ Å was derived from a velocity selector and double-focusing pyrolytic graphite monochromator on IN12. The neutrons were collimated by $\alpha = 80^\circ$ before scattering at the sample. On RITA-II, we used a wavelength $\lambda = 4.217$ Å. The high-energy background was minimized with a collimator ($\alpha = 80^\circ$), followed by a pyrolytic graphite filter before and a beryllium filter after the sample. The signal was recorded from the central analyzer blade of the RITA-II nine-bladed multianalyzer, and the background in Fig. 2 was obtained from the two neighboring blades.

The magnetic structure at zero field was obtained from the data measured on D10. Six independent magnetic Bragg reflections were analyzed using the three possible irreducible representations. The amplitude-measured on D10. Six independent magnetic Bragg reflections were analyzed using the three possible irreducible representations. The amplitude-measured on D10. Six independent magnetic Bragg reflections were analyzed using the three possible irreducible representations. The amplitude-measured on D10. Six independent magnetic Bragg reflections were analyzed using the three possible irreducible representations. The amplitude-measured on D10. Six independent magnetic Bragg reflections were analyzed using the three possible irreducible representations. The amplitude-measured on D10. Six independent magnetic Bragg reflections were analyzed using the three possible irreducible representations. The amplitude-measured on D10. Six independent magnetic Bragg reflections were analyzed using the three possible irreducible representations. The amplitude-measured on D10. Six independent magnetic Bragg reflections were analyzed using the three possible irreducible representations. The amplitude-measured on D10. Six independent magnetic Bragg reflections were analyzed using the three possible irreducible representations.
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Field-induced magnetic instability within a superconducting condensate

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