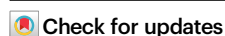


High-field-stabilized reentrant superconductivity in infinite-layer nickelate thin films

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Magnetic fields typically suppress superconductivity through Pauli and orbital limiting effects. However, there are rare instances of magnetic-field-induced superconductivity, as observed in Chevrel-phase compounds, organic conductors, uranium-based heavy-fermion systems, and moiré graphene—although these materials possess inherently low superconducting transition temperatures (T_c). Here, we demonstrate high-field-stabilized superconductivity in a class of materials recently shown to have significantly higher T_c values (up to 40 K): the infinite-layer nickelates. We show that both the low-field and high-field superconducting states can be understood in terms of a field-compensation mechanism, better known as the Jaccarino-Peter effect. These findings demonstrate the possibility of achieving substantially enhanced upper critical fields in high-temperature superconductors.

There is considerable technological interest in the superconducting state that remains robust in high magnetic fields^{1–3}. One significant challenge is that strong magnetic fields are typically detrimental to superconductivity. This occurs via two primary mechanisms: Pauli pair breaking^{4,5}, where the Zeeman interaction aligns electron spins and disrupts spin-singlet Cooper pairs, and orbital pair breaking, where magnetic flux penetrates the superconductor in the form of vortices, ultimately destroying phase coherence when the vortex density becomes too high⁶.

One possible way to circumvent the detrimental effects of magnetic fields on superconductivity is to exploit situations in which the interplay between conduction electrons and magnetism gives rise to magnetic-field-induced superconducting states^{7–14}. Discovered in Chevrel-phase compounds⁷, field-induced superconductivity has so far

been observed only in materials with intrinsically low superconducting transition temperatures (T_c). This limitation is often attributed to factors such as conventional electron-phonon-mediated pairing⁷ or the presence of narrow electronic bandwidths^{10,12,15}, which enhance electronic correlations but typically suppress T_c .

Here we demonstrate that infinite-layer nickelates^{16–19} provide an example of a magnetic-field-reentrant superconducting state persisting to very strong magnetic fields occurring in a material that also hosts high-temperature superconductivity comparable to that of the cuprates²⁰. Specifically, we observe this phenomenon in 4–7 nm-thick films of $(\text{Sm}_{1-x-y}\text{zEu}_x\text{Ca}_y\text{Sr}_z)\text{NiO}_2$, hereafter referred to as SECNO, which were recently shown to exhibit transition temperatures approaching $T_c \approx 40$ K¹⁹—exceeding that of the first cuprate system in which high- T_c superconductivity was originally discovered²¹.

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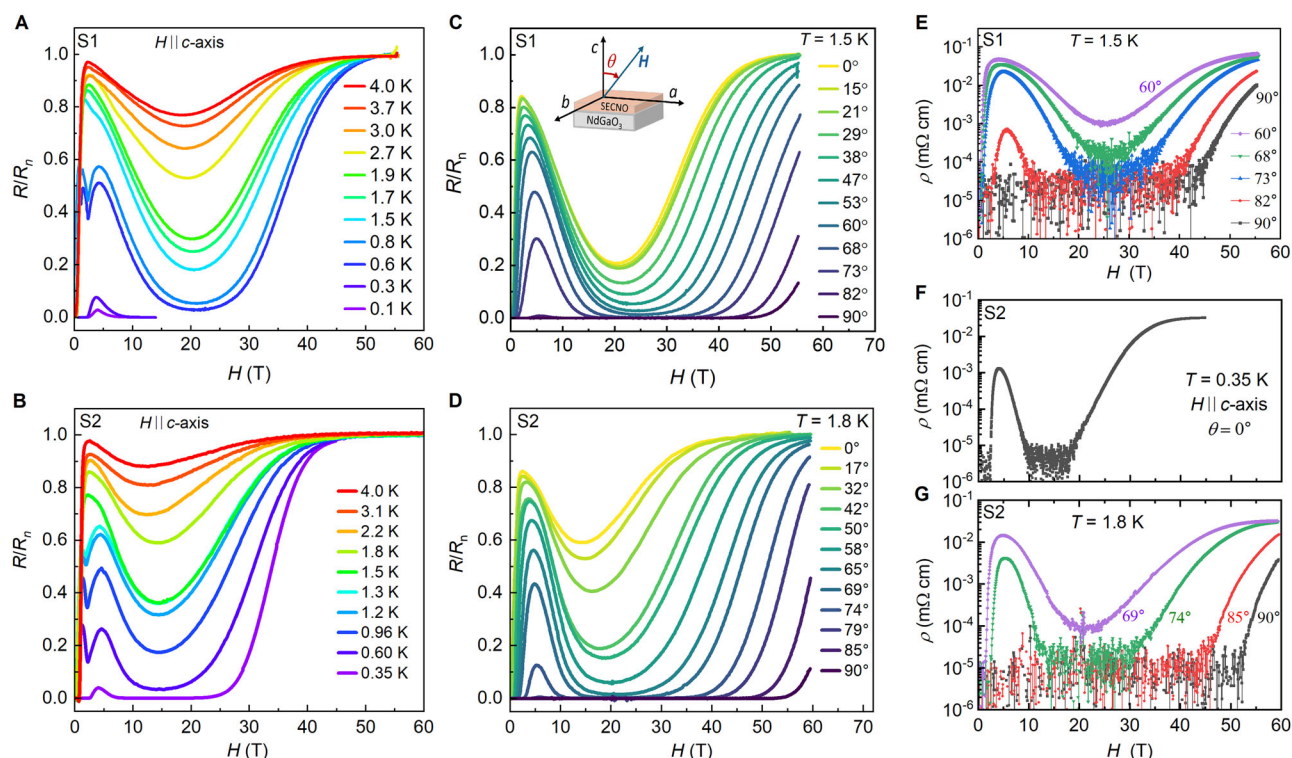


Fig. 1 | Re-entrant superconductivity at high magnetic fields in SECNO superconductors. **A** Measured renormalized electrical resistivity R/R_n versus magnetic field H of sample S1 ($T_c = 9.6$ K) at different temperatures T with H applied along the c -axis. **B** Similar data for sample S2 ($T_c = 11.7$ K). **C, D** R/R_n measured in both samples at constant temperature for different angles θ between the applied field and the c -

axis. The inset in (C) is a schematic of H alignment, moving away from the out-of-plane c -axis ($\theta = 0^\circ$) toward the in-plane a -axis ($\theta = 90^\circ$). **E–G** Absolute resistivity ρ plotted on a logarithmic scale, reveal it to drop by roughly four orders of magnitude. For compositions, see Table 1 in the Methods.

Results

Re-entrant superconductivity in SECNO

Figure 1 shows the experimental evidence for reentrant superconductivity in resistance curves measured for two SECNO samples, S1 and S2, with relatively low transition temperatures of $T_c \approx 9.6$ K and 11.7 K, respectively (see Methods and Table 1 for exact composition and film thickness). The resistance is measured as a function of magnetic field H at various temperatures T , with H applied along the crystalline c -axis (Fig. 1A, B). Salient features of both samples include a sharp transition from the superconducting to the resistive state at $H \approx 1$ T, followed by a small dip in resistivity near $H \approx 2$ T for $T < 2$ K. This dip coincides with the spin-flop transition of the antiferromagnetically ordered Nd moments in the NdGaO₃ substrate into a polarized state (see Supplementary Fig. 2 and Methods). At higher fields, a broad resistivity minimum emerges—centered around $H \approx 20$ T and 15 T for samples S1 and S2, respectively—which shifts systematically to higher fields as the tilt angle θ between H and the crystalline c -axis increases (see Fig. 1C, D and Supplementary Fig. 3). At sufficiently large fields, the resistivity rises and saturates at a nearly constant value, consistent with the normal state.

Suggestive of a reentrant superconducting state involving a substantial fraction of the thin nickelate films, the resistivity plotted on a logarithmic scale drops by several orders of magnitude (see Fig. 1E–G) and becomes dominated by noise at sufficiently low temperatures, $T \lesssim 0.35$ K at $\theta = 0^\circ$, at angles above $\theta \sim 70^\circ$ at $T = 1.5$ K in sample S1, or at angles above $\theta \sim 74^\circ$ (26°) at $T = 1.8$ K (0.6 K) in sample S2. The magnitude of the resistance drop at high fields is comparable to that observed in the low-field superconducting state at $H < 1$ T. Consistent with the presence of superconducting screening currents in the vanishing-resistivity regime of the thin films, radio-frequency (≈ 20 MHz) inductive measurements on sample S1—performed using

Table 1 | Compositional details for SECNO

Sample	T_c (K)	Film thickness (nm)	Composition
S1	9.6	6.5(5)	$\text{Sm}_{0.58}\text{Eu}_{0.35}\text{Ca}_{0.07}\text{NiO}_2$
S2	11.7	4.5(5)	$\text{Sm}_{0.53}\text{Eu}_{0.4}\text{Ca}_{0.07}\text{NiO}_2$
S3	16.8	6.5(5)	$\text{Sm}_{0.53}\text{Eu}_{0.4}\text{Ca}_{0.07}\text{NiO}_2$
S4	22.1	4.5(5)	$\text{Sm}_{0.79}\text{Eu}_{0.12}\text{Ca}_{0.04}\text{Sr}_{0.05}\text{NiO}_2$
S5	31.7	4.5(5)	$\text{Sm}_{0.73}\text{Eu}_{0.2}\text{Ca}_{0.07}\text{NiO}_2$

Here, T_c refers to the midpoint of the transition. Numbers in parentheses refer to the experimental uncertainty.

a proximity-detector tank circuit²² adapted for pulsed magnetic fields²³ at $T = 0.5$ K (see Supplementary Fig. 4)—reveal that the vanishing-resistivity state in high magnetic fields is accompanied by a diamagnetic shift associated with screening currents. The magnitude of this shift at high angles is comparable to that of the low-magnetic field ($H < 1$ T) superconducting state, providing compelling evidence of bulk superconductivity in high-field regimes.

Colored contour plots in Fig. 2 indicate regions where the resistivity vanishes (purple) and where it reaches its normal-state value (light green). Following the convention introduced in the first discovery of magnetic-field-reentrant superconductivity in Chevrel-phase compounds^{7,24}, T_c and H_c data points refer to the midpoints of the resistive transitions, where the resistivity is halfway between zero and its saturated normal-state value. The T – H phase diagrams (Fig. 2A, B) clearly reveal two distinct superconducting phases: a low-field superconducting state and a high-field-induced reentrant superconducting state. These two phases merge as the direction of H is rotated toward the in-plane a -axis (Fig. 2C, D and Supplementary Fig. 3B), with superconductivity persisting at least up to 60 T (50 T) at $T = 0.6$ K (1.5 and 1.8 K).

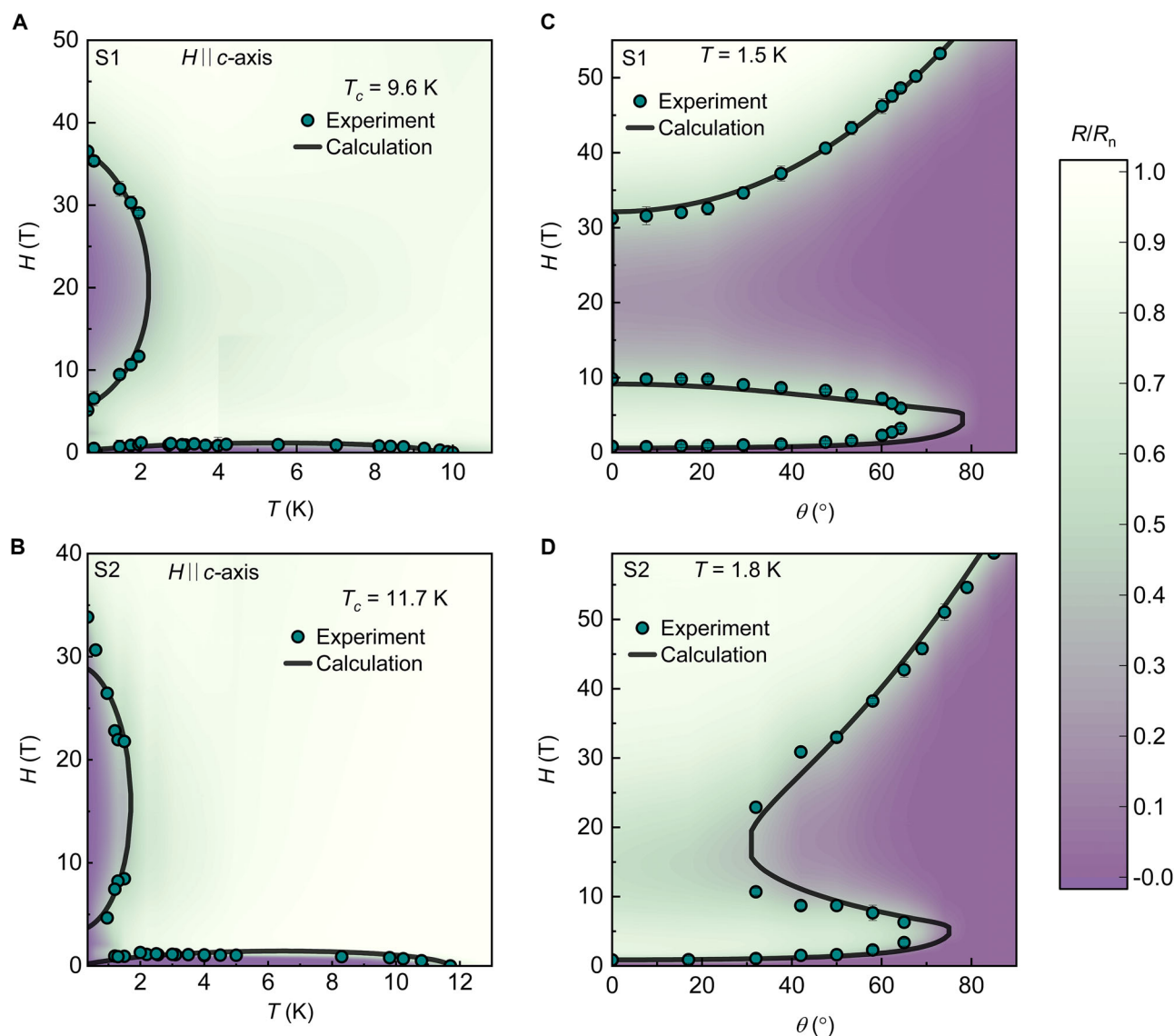


Fig. 2 | High-field reentrant superconductivity in SECNO: phase diagrams and evolution of upper critical field with temperature and tilt angle. Phase diagrams of critical magnetic field versus temperature of (A) S1 ($T_c = 9.6$ K) and (B) S2 ($T_c = 11.7$ K) for H parallel to the c -axis. Phase diagrams of critical magnetic field versus

angle θ of (C) S1 at $T = 1.5$ K and (D) S2 at $T = 1.8$ K. Symbols are experimentally determined phase boundaries delineated as the midpoints of the resistive transitions and lines are calculated phase boundaries using a modified WHH model.

The WHH model modified by Jaccarino-Peter compensation

The mechanisms underlying the reentrant superconductivity have been the subject of extensive debate. Proposed explanations include compensation of the applied field by an internal exchange field^{7,9,13}, electron pairing mediated by spin fluctuations^{10,25,26}, field-enhanced spin reorientation or spin-triplet pairing^{10,15}, field-induced magnetic transitions and Fermi-surface reconstructions²⁷, and Landau-level broadening near the quantum limit²⁸. Given the presence of rare-earth elements Sm and Eu within the nickelate films, or Nd within the substrate, it is plausible that field-induced reentrant superconductivity in SECNO arises from significant exchange interactions J_{cf} between the conduction electrons and localized rare-earth magnetic moments²⁹. In magnetic ion-containing superconductors (e.g., Eu-containing Chevrel-phase compounds^{7,30} and Fe-based organic conductors^{8,9}), the conduction electrons experience a negative internal exchange field $H_J - J_{cf}/\mu_B$ from the magnetic ions (where μ_B is the Bohr magneton). Because the internal exchange field aligns opposite to the applied magnetic field, the two can partially or completely cancel each other, thereby reducing the Pauli pair-breaking effect of the external field and

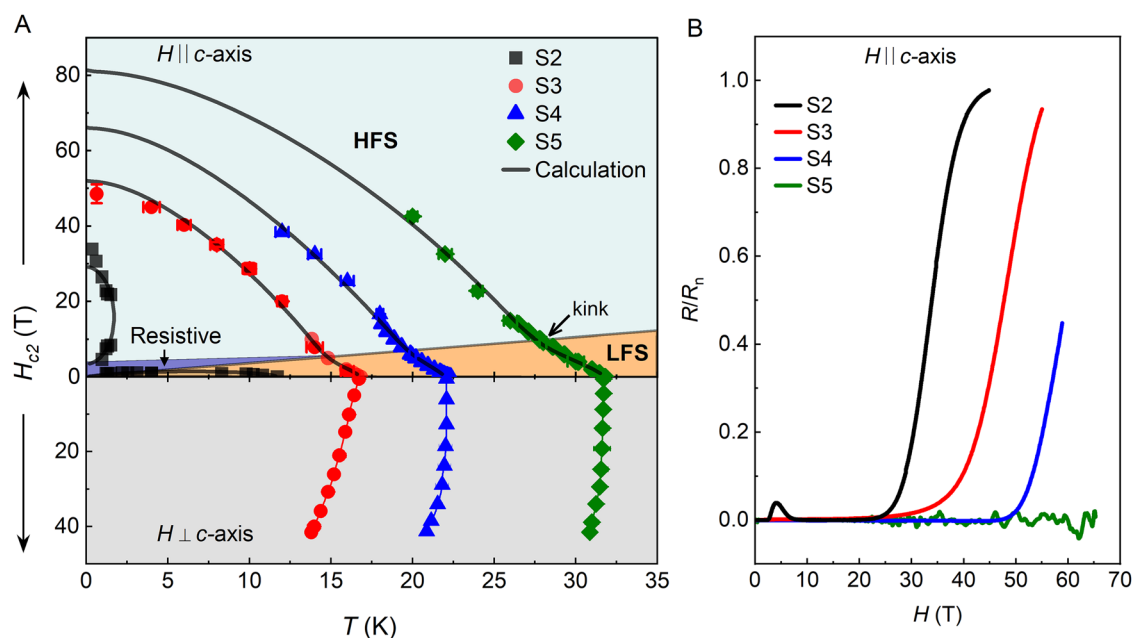
allowing a magnetic-field-induced superconducting phase to appear, centered around $H = |H_J|$. This magnetic-field compensation mechanism was predicted long before reentrant superconductivity was discovered and became known as the Jaccarino-Peter effect²⁹.

Clues to the relevant mechanism for reentrant superconductivity in SECNO are provided by striking similarities to the Chevrel-phase compounds in which reentrant superconductivity was first discovered^{7,24} when $H \parallel c$. These similarities are evident in both the resistivity curves (see Fig. 1) and the corresponding phase diagrams (see Fig. 2), constructed using the same midpoint-of-transition criterion. In the Chevrel-phase compounds, the combined effects of the orbital critical field H_c^{orb} and spin-orbit scattering (parameterized by λ_{SO}) are known to shift the reentrant superconducting state down in magnetic field so that its optimal (field-stabilized) T_c occurs at a magnetic field lower than $|H_J|$ ³⁰. These effects are treated using the Werthamer-Helfand-Hohenberg (WHH) model³¹, which is a microscopic model describing the upper critical field of conventional type-II superconductors in the dirty limit. Incorporating $|H_J|$ into the WHH model reproduces several key features of the magnetic field-

We find that the WHH model^{24,30}, modified to include $|H_J|$ ^{24,30}, provides an equally good description of the phase diagrams of SECNO shown in Fig. 2A, B, enabling us to estimate key parameters, such as the exchange field H_J , Maki parameter α , orbital critical field H_c^{orb} , and Pauli limiting field $H_p = \frac{\sqrt{2}}{q} H_c^{\text{orb}}$ (see Methods). For sample S1, we obtain a large exchange field $H_J \approx 59$ T, together with $\alpha \approx 3$, $H_c^{\text{orb}} \approx 43$ T, and $H_p \approx 20$ T (see Table 2 and Methods). For sample S2, a larger exchange field of $H_J \approx 71$ T is estimated (see Methods).

Sample	$H_c^{\text{orb}}(\text{T})$	λ_{so}	α	$H_J(\text{T})$	$H_p(\text{T})$
S1	43.1(3)	3.7(4)	3.00(10)	− 58.7(4)	20.3
S2	44.6(7)	5.5(9)	3.00(fixed)	− 70.7(1.2)	21.0
S3	52(2)	24(4)	3.7(2)	− 43(5)	20.1
S4	67(4)	28(7)	3.7(3)	− 49(6)	25.5
S5	83(5)	8.8(1.2)	3.0(3)	− 58(5)	38.9

The low- and high-magnetic-field-induced superconducting states merge not only when H is rotated into the planes but also when the transition temperature is increased by changing rare-earth substitution or varying film thickness, as demonstrated by the evolution of the phase diagram with increasing T_c (from 11.7 to 31.7 K) in the upper panel of Fig. 3A. The exact compositions and film thicknesses of all studied samples are listed in Table 1. The raw data from which the T_c and H_c points are extracted are shown in Supplementary Figs. 5 and 6. In the higher- T_c samples, this merging manifests as a kink in the phase boundary at fields below 10 T in the magnetic field-temperature (H - T) phase diagrams (upper panel of Fig. 3A)—a feature also observed in Chevrel-phase compounds with higher transition temperatures²⁴. Because this kink is fully reproduced by the WHH model (curved lines in Fig. 3A, see Methods), its presence provides a useful indicator of the crossover between distinct low-field (LFS) and high-magnetic-field-induced superconducting (HFS) states. For fields parallel to the c -axis and $T_c = 31.7$ K, the high-magnetic-field-induced superconducting state extends at least up to 65 T (Fig. 3B), as evidenced by the persistence of vanishing electrical resistivity up to this field.



background denotes the low-field superconducting (LFS) state, while the light-teal background represents the high-field-induced superconducting (HFS) state. The royal-blue region marks the resistive state that appears at intermediate fields for lower- T_c samples. The boundary line between the LFS and HFS regions highlights the emergence of a kink in the phase diagram. **B** Resistance normalized by the normal state value (R/R_n) measured at low temperatures of 0.35 K for S2, 0.6 K for S3, 0.6 K for S4 and 1.5 K for S5 for $H \parallel c$ axis.

Upon rotating the magnetic field into the planes ($H \perp c$), where the orbital critical field is expected to be larger, we find that the internal exchange field allows superconductivity to persist to extraordinarily high magnetic fields in the higher- T_c samples. The lower panel of Fig. 3A and Supplementary Fig. 8 show that increasing the magnetic field from zero to 42 T—above the Pauli limit (see Table 2)—suppresses T_c by a mere ~ 1 K in samples S4 ($T_c = 22.1$ K) and S5 ($T_c = 31.7$ K), indicating that superconductivity is boosted to magnetic fields far exceeding the Pauli limit.

Discussion

In support of a Jaccarino-Peter effect mechanism involving Eu magnetic moments in SECNO, analogous to that in Chevrel-phase compounds, our X-ray absorption spectroscopy measurements reveal that approximately 67% of the Eu sites are in the Eu^{2+} configuration (see Supplementary Fig. 7), in agreement with Ref. 33, suggesting a static mixed-valence state. Specifically, we find that the phase transition out of the low-magnetic-field superconducting phase (see Figs. 2 and 3 and Methods) is reproduced when using $m_j = \pm \frac{7}{2}$ for Eu^{2+} in the WHH model. Moreover, the form of the anomalous Hall effect in sample S1 measured above T_c closely matches the magnetization calculated from the Brillouin function for $m_j = \pm \frac{7}{2}$ of Eu^{2+} at the same temperatures (see Supplementary Fig. 7A, B). These results suggest that the tetragonal symmetry of the lattice produces a weak crystal electric field splitting at the Eu^{2+} sites. The close correspondence between the anomalous Hall effect and the Brillouin function in Supplementary Fig. 2A, B also indicates that there is no experimental evidence for ferromagnetism involving Eu^{2+} above T_c , although this does not preclude the possibility of a low-field magnetic state coexisting with superconductivity below T_c . Furthermore, while other rare-earth magnetic moments could in principle influence the phase diagram, their effect is expected to be much weaker than that of Eu^{2+} (see Methods).

Given the many reported parallels between the phase diagrams of the nickelates and cuprates^{34,35}, our finding that the nickelate phase diagram can be described by the WHH model provides important clues to the pairing mechanism. Since the WHH model, which successfully reproduces the data, is based on Bardeen-Cooper-Schrieffer (BCS) theory³⁶, this suggests that the superconducting pairing symmetry is even (i.e., non-triplet) and the BCS theory provides a useful starting point for understanding superconductivity in the nickelates. Nevertheless, open questions remain—for example, whether the theory must be revised to account for a possible unconventional s - or d -wave pairing symmetry, non-phonon-mediated pairing mechanisms, or strong fluctuation effects³⁷.

Given the experimental evidence for high-magnetic-field-induced superconductivity in SECNO, an important question arises: why have similar effects not been observed in other high-temperature superconductors, such as the cuprates or iron-based compounds? As in the nickelates, rare-earth elements are sometimes present in their spacer layers. In the cuprates, Gd^{3+} has the same magnetic configuration as Eu^{2+} , although magnetic-field-induced (or enhanced) superconductivity has not been reported in Gd-containing cuprates³⁸. Meanwhile, in Eu^{2+} -containing Fe-based superconductors^{39,40}, only a weak magnetic-field enhancement of superconductivity has been observed, and it does not arise via a compensation mechanism. One crucial distinction between the nickelates and both the cuprates and Fe-based superconductors is the participation of the rare-earth $5d$ electrons in the conduction bands⁴¹. This provides a plausible exchange path, $4f \leftrightarrow 5d \leftrightarrow 3d_{\text{Ni}}$, linking the transition-metal $3d$ conduction electrons and the rare-earth $4f$ magnetic moments⁴²—an interaction that is unlikely to exist in the cuprates or Fe-based superconductors. Whether this coupling is sufficient to produce the observed magnitude of the exchange field (with $|H_J|$ as high as 70 T) remains an open theoretical question.

In summary, we have discovered high-magnetic-field-reentrant superconductivity in an infinite-layer nickelate system, SECNO. Unlike previously known reentrant superconductors, whose low-field superconducting states typically exhibit low critical temperatures ($T_c < 4$ K)^{7,8,10,12,15}, SECNO displays superconductivity with T_c values reaching up to 40 K at ambient pressure¹⁹, comparable to that in several high- T_c cuprate families²⁰. Our measurements on multiple SECNO samples with varying T_c reveal magnetic-field-reentrant superconductivity in samples with low T_c (9.6–11.7 K), and evidence for a crossover between low-field and high-field superconducting states in samples with higher T_c (extending up to 31.7 K). In the latter, extraordinarily large critical magnetic fields are observed well beyond the Pauli paramagnetic limit (as estimated using the WHH model). In all cases, the behavior is consistent with a Jaccarino-Peter compensation mechanism. These findings outline a concrete pathway toward superconductors that operate at tens of tesla and establish high- T_c nickelates with engineered rare-earth magnetism as a realistic platform for ultra-high-field superconducting magnets, sensors, and quantum devices—qualitatively different from previous low- T_c reentrant superconductors.

Methods

Sample growth and characterization

The bulk targets of $\text{Sm}_{1-x-y}\text{Eu}_x\text{Ca}_y\text{NiO}_3$ were synthesized using a solid-state reaction of Sm_2O_3 (99.999%, Sigma-Aldrich), Eu_2O_3 (99.999%, Sigma-Aldrich), CaCO_3 (99.995%, Sigma-Aldrich), and NiO (99.99%, Sigma-Aldrich) powders according to the stoichiometric ratio. In each stage of sintering, the powder mixture were fine ground before annealed at 1200 °C, 1300 °C, and 1400 °C consecutively for 12 h, 15 h, and 18 h, respectively, using a chamber furnace. Finally, the mixture was pelletized into a bulk disk-shaped target ready for pulsed laser deposition (PLD). $\text{Sm}_{1-x-y}\text{Eu}_x\text{Ca}_y\text{NiO}_3$ films were grown by PLD on NdGaO_3 substrate with a KrF excimer laser (248 nm wavelength) at a substrate temperature of 650 °C along with a partial oxygen pressure of 200 mTorr in the chamber and a laser fluence of 2.6 J cm⁻². We have established an improved topotactic reduction setup, which allows in-situ resistivity (I - V) monitoring during the reduction process, compared to the methodology used in ref. 19. From there, we can precisely determine the reduction time for achieving optimally reduced infinite-layer phase. The schematic of this setup and corresponding resistivity with time for sample S3 is shown below in Supplementary Fig. 1A, B, respectively. As shown in Supplementary Fig. 1A, the as-grown sample was attached to the heater chip of the Linkam system using silver paste and dried with a low-temperature profile (60 °C–120 °C) for approximately 35 minutes. Four-point contact electrodes were made using an ultrasonic Al wire-bonder for in-situ resistance monitoring with a LabVIEW program connected to a Keithley 2400 source meter. CaH_2 powder was ground and placed in tandem with the mounting sample in the Linkam chamber, which was evacuated before running the reduction heating profile at 310 °C.

During the reduction process, the crystal structure evolves gradually, while the resistance initially increases with temperature, reaching $\sim 10^2 \Omega$, and then gradually decreases to a plateau as depicted in Supplementary Fig. 1B. Based on our experimental experience, this plateau corresponds to the completion of the reduction process. The reduction time depends on the as-grown film quality, sample geometry, and film thickness, and may vary between samples. This means our latest reduction method is critical for optimally reduced samples, such as $\text{Sm}_{0.53}\text{Eu}_{0.4}\text{Ca}_{0.07}\text{NiO}_2$. Supplementary Fig. 1C shows the XRD data of $\text{Sm}_{0.53}\text{Eu}_{0.4}\text{Ca}_{0.07}\text{NiO}_2$ (sample S3) during reduction optimization at different reduction stages: under-reduced and optimally reduced. The data clearly illustrate the structural evolution from the perovskite to the infinite-layer (IL) phase via a topotactic reduction. During heating with CaH_2 , hydrogen is generated, gradually removing the apical oxygen from the perovskite lattice and hence the c -axis will

shrink. In the under-reduced sample (magenta curve), the (001) peak of perovskite ($2\theta \sim 24^\circ$) coexisted with the (001) peak of the infinite-layer phase ($2\theta \sim 27^\circ$), indicating that apical oxygen is only partially removed. At this stage, the sample is not homogeneous. In the optimally reduced sample (purple curve), the perovskite phase is fully converted to the infinite-layer structure, with no detectable remnants from the perovskite phase, demonstrating the completion of the reduction process. The film thicknesses are estimated from the number of deposition laser pulses, with the growth rate calibrated by cross-sectional scanning transmission electron microscopy (STEM) in terms of deposition pulses per unit thickness⁴³.

The x-ray absorption spectroscopy (XAS) was measured using linearly polarized X-rays from the soft X-ray-ultraviolet (SUV) beamline at Singapore Synchrotron Light Source (SSLS). A total electron yield (TEY) detection method was used during the measurements.

Measurements

Samples were wire-bonded using an ultrasonic wire bonder for electrical transport measurements. High-field transport measurements were performed at both the DC and pulsed-field facilities of the National High Magnetic Field Laboratory. Pulsed-field measurements in the temperature range 4–0.5 K were conducted using a 60 T ‘Mid-pulse’ pulsed magnet with a pulse duration of ~ 500 ms and a 70 T ‘Duplex’ pulsed magnet with a pulse duration of ~ 60 ms. High DC-field measurements were carried out using a ‘45 T Hybrid’ magnet for temperatures below 0.5 K and using a ‘42 T Resistive’ magnet for temperatures 1.5–35 K. Additional measurements in DC magnetic fields up to 14 T were performed using a PPMS from Quantum Design Inc at temperatures above 1.5 K and in a dilution fridge at temperatures down to 0.1 K. To minimize heating induced by eddy current and magnetocaloric effect during pulsed-field measurements, we used samples of size $\sim 0.5 \times 0.5$ mm² and adopted the van der Pauw method. Measurements above 4 K were done in ⁴He gas in DC magnetic fields. Measurements between 4 and 1.5 K were conducted by immersing the samples in liquid ⁴He, while those below 1.5 K were performed in liquid ³He or in liquid mixture of ³He and ⁴He. A standard lock-in technique was used for all transport measurements. Home-made rotators were used for in-situ rotation of samples in magnetic fields.

The Hall resistance (Supplementary Fig. 2A) was measured using the van der Pauw method in a PPMS by applying an excitation current of 10 μ A and measuring the voltage across the diagonal contacts.

The magnetization of the 500 μ m thick NdGaO₃ substrate along the $\langle 110 \rangle$ orientation in Supplementary Fig. 2C was measured in pulsed magnetic fields using a susceptometer constructed from counterwound coils and in DC magnetic fields using a SQUID magnetometry. The DC magnetization was measured using a Quantum Design Magnetic Properties Measurement System (MPMS) with an ³He insert. The sample was mounted with Dow-Corning high-vacuum grease on a copper sample holder of uniform density along the axis of transport inside a plastic drinking straw lined with copper wires for thermal stability. The entire magnetically uniform ³He sample chamber is moved through the SQUID pickup coils by the standard MPMS transport system.

Because the nickelate thin film is deposited on a magnetic NdGaO₃ substrate—and its volume is $\sim 10^5$ times smaller than that of the substrate—conventional measurements, such as magnetic susceptibility and specific heat cannot reliably isolate the film’s signal. For this reason, we employed tank circuit measurements. These measurements were performed in the Midpulse magnet under the same experimental conditions used for transport measurements. Here, a proximity detector tank circuit²³ was transformer coupled to a 6 turn pancake coil wound from 50 gauge copper wire, to which the sample could be attached, resonating at ~ 20 MHz. Screening within the sample modified the inductance on the coil, leading to a diamagnetic frequency shift. To enable digitization for ~ 500 ms pulse of magnetic fields, the

radio frequency oscillations were mixed down to a lower frequency below ~ 2 MHz. For the reentrant superconducting state, the observation of a diamagnetic frequency shift in the sample required subtraction of a background measurement at the same θ and temperatures without the sample present. The form of magnetic field-dependent background observed without the sample is the result of magnetoresistance in the copper wire forming the coil that itself causes the tank circuit frequency to change with magnetic field.

Theoretical model

We employ the Werthamer-Helfand-Hohenberg (WHH) model³¹, a microscopic theory that describes the upper critical magnetic field of conventional type-II superconductors in the dirty limit, incorporating the influence of localized magnetic impurities to both orbital and paramagnetic pair-breaking effects and to spin-orbit scattering. The implicit equation we used to fit experimental H_c as a function of temperature (Fig. 2A) is^{24,31}

$$\ln \frac{1}{t} = \left(\frac{1}{2} + \frac{i(\lambda_{so} - \lambda_m)}{4\lambda} \right) \times \psi \left(\frac{1}{2} + \frac{h + \lambda_m + \frac{1}{2}(\lambda_{so} - \lambda_m) + i\lambda}{2t} \right) + \left(\frac{1}{2} - \frac{i(\lambda_{so} - \lambda_m)}{4\lambda} \right) \times \psi \left(\frac{1}{2} + \frac{h + \lambda_m + \frac{1}{2}(\lambda_{so} - \lambda_m) - i\lambda}{2t} \right) - \psi \left(\frac{1}{2} \right) \quad (1)$$

where $\lambda = \left[\alpha^2(h + h_j)^2 - \frac{1}{4}(\lambda_{so} - \lambda_m)^2 \right]^{1/2}$. The parameters formulated in reduced units are: $t = \frac{T}{T_c}$, $h = 0.281 \frac{H_c(T)}{H_c^{orb}}$, and $h_j = 0.281 \frac{H_j(T)}{H_c^{orb}}$, where T_c is the critical SC transition temperature, H_c^{orb} is the orbital-limited critical field at absolute zero temperature (for H perpendicular to the planes), H_j is the exchange field described by a Brillouin function for Eu²⁺ ions. The above numerical factor of 0.281 is obtained theoretically by solving the gap equation in the presence of Pauli limiting (in the limit $\lambda_{so} \rightarrow 0$)³¹. Meanwhile, λ_{so} and λ_m are the spin-orbit and magnetic scattering parameters, respectively. ψ is the digamma function with a complex argument, and α is the Maki parameter given by $\alpha = \sqrt{2} \frac{H_c^{orb}}{H_p}$ with H_p being the Pauli-limited critical field.

The low upper critical field ~ 1 T is reproduced when H_j saturates very rapidly at magnetic fields lower than 1 T. Such behavior is most accurately reproduced when $m_j = \pm 7/2$ for the Eu²⁺ magnetic moments, suggesting the presence of weak crystal electric field effects in the nickelate films. This implies that the effective g -factor should also scale as $\cos \theta$ for $\theta < 90^\circ$. Below we further find that a $\cos \theta$ behavior of the effective g -factor enables the θ -dependence of the critical field of the low magnetic field superconducting phase to be understood.

Assuming $\lambda_m = 0$ and using the fitting parameters H_c^{orb} , λ_{so} , α , and H_j (listed in Table 2) – we can produce the key features of the experimental data for sample S1, including low-field and high-field superconducting states, as shown in Fig. 2A and Fig. 2B. For sample S2, owing to the lower temperature of its reentrant phase, allowing all parameters to vary yielded $\alpha = 5(3)$ and a large uncertainty in λ_{so} , but not H_j (its saturated high field value) or H_c^{orb} . We therefore repeated the fitting, holding α at the same value as determined for S1, where it was well-constrained.

The steep increase in H_c below 0.6 K remains unexplained using the simplified WHH model and, therefore, needs elaborate theory efforts that is beyond the scope of this work. Notably, low-temperature non-saturating H_c has also been reported in other nickelates^{44,45} and cuprates^{46,47} and various mechanisms, including an interplay between superconductivity and a density wave⁴⁸ and the existence of multiple bands⁴⁹, are proposed to account for this phenomenon.

We find that the angle-dependent phase diagram (Fig. 2C and D) can be reproduced by using the Tinkham formula

$$\left| \frac{H_{c,\perp}^{\text{orb}}(\theta) \cos \theta}{H_{c,\perp}^{\text{orb}}} \right| + \left(\frac{H_{c,\parallel}^{\text{orb}}(\theta) \sin \theta}{H_{c,\parallel}^{\text{orb}}} \right)^2 = 1 \quad (2)$$

for the orbital critical field of a two-dimensional superconductor, where $H_{c,\perp}^{\text{orb}}$ and $H_{c,\parallel}^{\text{orb}}$ are the orbital critical fields perpendicular and parallel to the planes, respectively. Note also that $\alpha(\theta) = \sqrt{2}H_{c,\perp}^{\text{orb}}(\theta)/H_p$, meaning that the Maki parameter has the same angular dependence as the orbital critical field if H_p is isotropic.

For sample S1, we find $H_{c,\parallel}^{\text{orb}} = 71.8(0.5)$ T, whereas for sample S2 we find $H_{c,\parallel}^{\text{orb}} = 68.8(0.5)$ T. This suggests that the *c*-axis coherence length is smaller than the layer spacing in infinite-layer nickelates³². In the model, we also find that both H_p and the high magnetic field saturated value of H_f must be isotropic (to within ~1%) to account for the observed θ -dependence of the phase boundary of the field-induced superconducting phase.

Comment on the possible involvement of other rare-earth moments

Sm^{3+} moments ($J = \frac{5}{2}$, $g_J = \frac{2}{5}$) present in the infinite-layer nickelate thin films possess a small *g*-factor and therefore are expected to saturate only in fields of several tens of tesla, yielding a relatively small effective magnetic moment. Meanwhile, the NdGaO_3 substrate, where the Nd sites adopt the Nd^{3+} configuration ($J = \frac{9}{2}$, $g_J = \frac{8}{11}$), orders antiferromagnetically below ≈ 1.2 K. However, because the NdGaO_3 magnetization saturates via a spin flop transition at $H \approx 2$ T (see Supplementary Fig. 2C), an exchange coupling to conduction electrons near the film–substrate interface could be a factor in the sharp dip in resistivity observed at this field at low temperatures.

Data availability

The raw data used in this study have been deposited in the Zenodo database and is available on <https://doi.org/10.5281/zenodo.20636178>. The supplementary data that support the findings of this study are available from the corresponding authors upon request.

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Author contributions

K.R., K.Y.Y., A.A., and N.H. conceived and designed the project. N.F., G.X., S.P., and S.L.E.C. grew nickelate thin films and performed material characterization measurements under the guidance of A.A. K.R. and E.K. conducted transport measurements in high pulsed magnetic fields. K.R., K.Y.Y., and D.G. performed measurements in high DC magnetic fields. K.R., K.Y.Y., and S.M.T. measured transport in moderate fields in PPMS and dilution fridge. T.F.P. conducted supplemental transport measurements in dilution fridge under the guidance of S.K.G. K.R., A.P.D., O.E.A.V., and N.H. conducted magnetization measurements. K.R., M.K.C., and N.H. carried out proximity-detector tank circuit

measurements in high pulsed magnetic fields. C.S.T. conducted the X-ray adsorption spectroscopy measurements and G.X. analyzed the data under the guidance of MBHB. NH performed theoretical calculations. K.R., K.Y.Y., A.A., and N.H. analyzed the data and wrote the manuscript with input from all authors.

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Competing interests

The authors declare no competing interests.

Additional information

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