Intrinsic magnetism in superconducting infinite-layer nickelates

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The discovery of superconductivity in Nd0.8Sr0.2NiO2 (ref. 1) introduced a new family of layered nickelate superconductors that has now been extended to include a range of strontium doping1–3, praseodymium or lanthanum in place of neodymium4–6, and the five-layer compound Nd5NiO12 (ref. 7). A number of studies have indicated that electron correlations are strong in these materials8–10, a feature that often leads to the emergence of magnetism. Here we report muon spin rotation/relaxation studies of a series of superconducting infinite-layer nickelates. Regardless of the rare earth ion or doping, we observe an intrinsic magnetic ground state arising from local moments on the nickel sublattice. The coexistence of magnetism—which is likely to be antiferromagnetic and short-range ordered—with superconductivity is reminiscent of some iron pnictides11 and heavy fermion compounds12, and qualitatively distinct from the doped cuprates13.

Monovalent 3d9 nickelates (NiI+2) such as LaNiO2 have long been considered in the context of divalent 3d9 cuprates (CuI+2)14–17. Despite being isostructural to the infinite-layer (Sr,Ca)CuO2 system, it is not yet clear how similar the two families really are. The cuprates are charge-transfer insulators, and doped holes appear in the O 2p-band, while Cu retains its 3d9 character—a situation described by the Zhang–Rice singlet18. In nickelates, there is a larger charge-transfer gap, so the system is closer to a Mott insulator, and holes reside more predominantly in the Ni 3d-band19–21. An additional aspect to consider in the nickelates is nickel–rare earth hybridisation22.

A notable difference is that the parent compounds of the superconducting cuprates are long-range-ordered antiferromagnets; upon doping, dispersive magnetic excitations persist across the superconducting dome23. By contrast, no long-range magnetic order has been observed in the bulk compounds LaNiO2 and NdNiO2 (refs. 24, 25). However, magnetic excitations consistent with the magnon dispersion expected for cuprate-like antiferromagnetic order have recently been observed in NdNiO2 films26. These features are already heavily damped, and, upon doping, their visibility is rapidly lost. It is therefore an open question as to whether magnetism is relevant for the superconducting dome in the nickelates. To investigate this, muon spin rotation/relaxation (μSR) is ideal. This is a highly local probe that also provides magnetic volume information, and is free from complications due to the possible role of magnetic defects or interfacial effects. Furthermore, through a comprehensive study of four infinite-layer compounds (Nd0.8Sr0.2NiO2, Pr0.8Sr0.2NiO2, La0.8Sr0.2NiO2 and LaNiO2), the contribution, if any, of the rare earth moment can be disentangled, as NdI+2 and PrI+2 contain 4f electrons, but LaI+2 does not.

μSR involves a beam of spin-polarised, positively charged muons μ+ implanted into a sample (Fig. 1a). Any component of the local magnetic field B that is transverse to the muon spin will cause it to precess with Larmor frequency γμ/μB, where γμ is the gyromagnetic ratio of the muon. Muons decay, via the weak force with a mean lifetime of 2.2 μs, into a positron, a neutrino and an antineutrino. The positron is emitted preferentially along the direction of the muon spin at the moment of its decay, and if the spin of the muon ensemble is precessing, so too will the positron emission direction. Recording the angular distribution of the positrons as a function of the time that the muon spent in the sample thus provides information on the local B. μSR can be used to probe the intrinsic field in the sample (‘zero field’, ZF), or a weak magnetic field transverse to the muon spin can be applied externally. Both approaches are used here.

An important technical issue arises from the fact that high-quality crystalline, superconducting, infinite-layer nickelates are currently limited to thin films with a thickness of ~10 nm, and they often require a capping layer for stability (SrTiO3 is both the substrate and capping layer in these experiments). By decreasing the muon beam energy down to a few kiloelectronvolts, the stopping depth is reduced to the required nanometre scale. However, below 2 keV, a substantial fraction of the muons are lost due to backscattering and reflection. We thus used the capping layer thickness and Monte Carlo simulations to design optimal heterostructures and beam energies for 8-nm-thick nickelate layers. All sample parameters, as well as the beam energy used for each sample, are provided in the Supplementary Information. Figure 1b,c shows representative calculated muon stopping profiles for the Nd0.8Sr0.2NiO2 sample.

Using this approach, we measured the ZF asymmetry of the four infinite-layer nickelate compositions at various temperatures down to 5 K (Fig. 2a–d). A clear temperature dependence is observed, indicating the appearance of local magnetism. No ZF precession is observed, suggesting dephasing due to a broad field distribution and/or relaxation due to fluctuations.

The high-temperature spectra are Gaussian-like, as expected for only nuclear damped ZF spectra27. Meanwhile, the magnetic state—in the absence of ZF precession signals—can often be described by a bi-exponential decay. As discussed in the Supplementary

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Also shown is the fraction of backscattered muons (red). The dashed line at 4.5 keV is the optimal energy for the Nd$_{0.825}$Sr$_{0.175}$NiO$_2$ sample.

Fig. 1 | Features of the low-energy muon spin rotation experiment. a, Schematic of the $\mu$SR set-up. The green arrow denotes the muon spin, which precesses in a transverse field (whether applied or intrinsic) and the yellow arrow illustrates the corresponding positron emission direction. The electron neutrino ($\nu_e$) and muon antineutrino ($\bar{\nu}_\mu$) that are produced are also sketched in blue. Positron detectors are positioned 360° around the sample, but only one is shown for simplicity. b, Simulated muon implantation profiles (a total of 200,000 muons) for the Nd$_{0.825}$Sr$_{0.175}$NiO$_2$ sample with a 20-nm SrTiO$_3$ capping layer. c, The simulated fraction of implanted muons in Nd$_{0.825}$Sr$_{0.175}$NiO$_2$ (green), the SrTiO$_3$ cap (grey) and the SrTiO$_3$ substrate (black), as a function of implantation energy. Also shown is the fraction of backscattered muons (red). The dashed line at 4.5 keV is the optimal energy for the Nd$_{0.825}$Sr$_{0.175}$NiO$_2$ sample.

Fig. 2 | ZF muon decay asymmetry and fit parameters. a–d, Asymmetry in ZF at various temperatures for Nd$_{0.825}$Sr$_{0.175}$NiO$_2$ (a, $E=4.5$ keV), Pr$_{0.8}$Sr$_{0.2}$NiO$_2$ (b, $E=2.3$ keV), La$_{0.8}$Sr$_{0.2}$NiO$_2$ (c, $E=2.8$ keV) and LaNiO$_2$ (d, $E=2.3$ keV). Grey dashed lines mark the background asymmetry values. Error bars represent 1 s.d. of a Poisson distribution for each time bin. e, The $\beta$ parameter from fits to equation (1) as a function of temperature for the four samples. Lines serve as guides to the eye. Coloured regions indicate $\beta$ values for different forms of magnetism. Error bars represent one standard deviation from the fit.

Information, this is not a satisfactory description of our data. We therefore analysed the ZF data with the following function:

$$A_{ZF}(t) = A_0 \left[ (1 - \alpha) \exp(-\lambda_0 t) + \alpha \exp(-\lambda_3 t^\beta) \right] + A_{bg}.$$  

(1)

Here, $t$ is the time in microseconds, $A_0$ is the ‘initial’ asymmetry and $A_{bg}$ is an energy-dependent background contribution. The parameter $\alpha$ is temperature-dependent ($\alpha=1$ in the paramagnetic state), and $\lambda_0$ and $\lambda_3$ are the fast and slow depolarisation rates.

In the high-temperature limit, $\alpha$ goes to zero, and the exponent $\beta \approx 2$. For all samples, there is a loss in the ‘initial’ asymmetry with decreasing temperature (Supplementary Fig. 5a), which is a strong indication of a magnetic transition or crossover. This is supported by a concomitant increase of $\lambda_3$ (Supplementary Fig. 5b). Furthermore, as can be seen in Fig. 2a (Nd$_{0.825}$Sr$_{0.175}$NiO$_2$) and Fig. 2c (La$_{0.8}$Sr$_{0.2}$NiO$_2$), the $T=5$ K data at long times are above the
T = 100 K data. This is consistent with the formation of a static (on the timescale of the muon) magnetic ground state. For Pr$_{0.8}$Sr$_{0.2}$NiO$_2$ (Fig. 2b) and LaNiO$_2$ (Fig. 2d) this is less obvious, and the ground state may still be dominated by short-range magnetic correlations. The β exponent of the slow depolarising part of equation (1) is plotted in Fig. 2e. Although the temperature trends of the asymmetry are similar between the samples, Nd$_{0.825}$Sr$_{0.175}$NiO$_2$ shows a stronger influence of Nd moments at low temperatures. The paramagnetic asymmetry $A_{PM}$ is estimated as the point towards a spin-glass-like ground state or the influence of Nd moments in the heterostructure.

ZF μSR therefore shows that all the samples exhibit some form of intrinsic low-temperature magnetism. For Nd$_{0.825}$Sr$_{0.175}$NiO$_2$, Pr$_{0.8}$Sr$_{0.2}$NiO$_2$ and La$_2$NiO$_4$, the 5-K measurement is within the superconducting state (Supplementary Information), so this provides direct evidence for coexisting superconductivity and magnetism in infinite-layer nickelates. To determine whether this coexistence is relevant down to the microscopic level, weak transverse field (wTF) μSR measurements were performed to obtain the magnetic volume fraction of these samples.

The muon acts as a local magnetic sensor and there are two extremal cases under an applied transverse magnetic field. (1) If the internal field is much smaller than the applied field, the muon spin ensemble dominantly experiences the applied field. In this case, the muon spin precession is around the applied field and has a maximal amplitude (asymmetry). (2) If the local magnetic field distribution at the muon site is comparable to or stronger than the applied field, the muon spin ensemble dephases very rapidly. Therefore, the amplitude of the asymmetry of the resulting muon precession is proportional to the non-magnetic volume fraction of the sample. Each measurement, from 5 K up to room temperature, consists of at least two million events and is performed in a 10-mT field applied transverse to the initial muon spin polarisation.

Figure 3a–c displays the oscillations arising from the muon precession across the transverse field for Nd$_{0.825}$Sr$_{0.175}$NiO$_2$ at 250, 50 and 15 K. The solid lines represent a decaying cosine fit:

$$A_{TF}(t) = A_0 e^{-\lambda t} \cos(f_{\mu}Bt + \phi).$$

Here, $\phi$ is the relative detector phase with respect to the initial muon spin orientation. With decreasing temperature, the decreasing initial asymmetry $A_0$ as well as the increasing depolarisation rate $\lambda$ both indicate the increase of local moments at low temperatures. From $A_0$ the magnetic volume fraction, $F_M$, can be calculated as

$$F_M(T) = 1 - \frac{A_0(T)}{A_{PM}}.$$

To evaluate $F_M$ it is assumed that the high-temperature saturation of $A_0$ corresponds to a paramagnetic state and only nuclear moments remain. The paramagnetic asymmetry $A_{PM}$ is estimated as the mean of the initial asymmetries above 200 K. Figure 3d–g plots $F_M$, both indicate the increase of local moments at low temperatures. The overshoot and the kink at ~100 K for Pr$_{0.8}$Sr$_{0.2}$NiO$_2$ are not understood at this point.

The full magnetic volume fraction at low temperature agrees well with the picture suggested by the ZF measurements that the superconducting infinite-layer nickelates are intrinsically magnetic, and further reinforces the conclusion that superconductivity and magnetism coexist, with phase separation only a possibility on the scale of a few nanometres or less.

Finally, the implantation energy can be varied as a proxy for a depth scan. This was carried out for all four samples at 15 K (Fig. 4). Each panel in Fig. 4 shows the initial asymmetry (left axis) and the simulated fraction of muons (right axis) implanted in the nickelate layer, as a function of energy. For all four samples, the energy-dependent trend is similar, with a minimal asymmetry coinciding with the maximal muon implantation into the nickelate layer. Furthermore, when $E \gtrsim 10$ keV, the asymmetry begins to saturate at ~0.04–0.05. This behaviour can be fitted with a simple model based on the calculated implantation profiles and assuming step-function changes in the asymmetry at the interfaces in the heterostructure.
Fig. 4 | Depth scans of the wTF asymmetry. a–d, wTF muon decay asymmetry at 15K as a function of energy for Nd$_{0.825}$Sr$_{0.175}$NiO$_2$ (a), Pr$_{0.8}$Sr$_{0.2}$NiO$_2$ (b), La$_{0.8}$Sr$_{0.2}$NiO$_2$ (c) and LaNiO$_2$ (d). The right axis is the fraction of the total implanted muons that are stopped in the nickelate layer as determined from Monte Carlo simulations. The dashed and solid lines are fits to the experimental data assuming sharp changes of asymmetry at the interfaces in the multilayer (dashed lines) and allowing the asymmetry to ‘leak’ across the interfaces (solid lines), as described in the text and the Supplementary Information. The vertical dotted lines represent the central energies that are used for the temperature-dependent measurements in Figs. 2 and 3. Uncertainties representing 1 s.d. from the fit are smaller than the plot markers.

is allowed to penetrate into the substrate, that is, representing demagnetising fields, the fit result is given by the solid lines. These minimal models agree well with each other and with the experimental data, suggesting that the magnetic properties change sharply close to the interfaces between the nickelate layer and the SrTiO$_3$ on either side. This indicates that long-range demagnetising fields, as would be expected from a ferromagnetic thin film, are minimal in these nickelates. The energy dependence, therefore, suggests that the intrinsic magnetism in the infinite-layer nickelates is based on an antiferromagnetic coupling. More details on this model are provided in the Supplementary Information.

This depth-dependent information (together with the temperature dependence of the wTF and ZF spectra) offers clear evidence of intrinsic magnetism in infinite-layer nickelates. We now briefly discuss the implications of our work.

The undoped LaNiO$_2$ sample is magnetic with ~100% volume fraction at low temperature, despite the absence of a magnetic moment on the La$^+$ ion. This observation, combined with the close similarity of the ZF and wTF results upon exchanging the rare earth, indicates that the observed magnetism originates from the nickel sublattice.

The temperature dependence of $F_M$ shows that the magnetism sets in gradually. This, together with the lack of ZF precession, suggests that the magnetic state is not static long-range-ordered and that fluctuations (faster than the muon decay timescale) may be present and short-range correlations may dominate. This is consistent with previous reports of a lack of long-range order in the undoped infinite-layer nickelates.

The short-range-ordered and glassy behaviour that we report here is reminiscent of some cuprate superconductors where the spin-glass state, with increased hole doping, persists into the superconducting dome. However, a striking difference in this context is that the spin glass in cuprates usually appears at $T < 30 K$, much lower than observed here in nickelates, where an evolution begins already at ~150 K. This is despite the larger superexchange energies of cuprates ($100 \lesssim J \lesssim 150 meV$) in comparison to nickelates ($50 \lesssim J \lesssim 100 meV$). This high-temperature scale is more similar to the antiferromagnetic transition temperature of many iron pnictides, where magnetic order and superconductivity coexist.

Our work demonstrates that the family of infinite-layer nickelates is intrinsically magnetic, including in the superconducting state. This coexistence, together with the high temperature at which magnetism starts to set in, highlights a distinction from the nominally similar cuprates and suggests a more complex picture where the multi-orbital nature of the nickelates may play an important role.

Online content
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References
1. Li, D. et al. Superconductivity in an infinite-layer nickelate. Nature 572, 624–627 (2019).
2. Li, D. et al. Superconducting dome in Nd$_{1-x}$Sr$_x$NiO$_2$ infinite layer films. Phys. Rev. Lett. 125, 027001 (2020).
3. Zeng, S. et al. Phase diagram and superconducting dome of infinite-layer Nd$_{1-x}$Sr$_x$NiO$_2$ thin films. Phys. Rev. Lett. 125, 147003 (2020).
4. Osada, M. et al. A superconducting praseodymium nickelate with infinite layer structure. Nano Lett. 20, 5735–5740 (2020).
5. Osada, M., Wang, B. Y., Lee, K., Li, D. & Hwang, H. Y. Phase diagram of infinite layer praseodymium nickelate Pr$_{1-x}$Sr$_x$NiO$_2$ thin films. Phys. Rev. Mater. 4, 121801 (2020).
6. Osada, M. et al. Nickelate superconductivity without rare-earth magnetism: (La,Sr)NiO$_2$. Adv. Mater. 33, 2104083 (2021).
7. Zeng, S. et al. Superconductivity in infinite-layer nickelate La$_{1-x}$Ca$_x$NiO$_3$ thin films. Sci. Adv. 8, eabj9927 (2022).
8. Pan, G. A. et al. Superconductivity in a quintuple-layer square-planar nickelate. Nat. Mater. 21, 160–164 (2022).
9. Botana, A. S. & Norman, M. R. Similarities and differences between \(\text{LaNiO}_2\) and \(\text{CaCuO}_2\) and implications for superconductivity. *Phys. Rev. X* **10**, 011024 (2020).

10. Kitatani, M. et al. Nickelate superconductors—a renaissance of the one-band Hubbard model. *npj Quantum Mater.* **5**, 59 (2020).

11. Wu, X. et al. Robust \(d_{x^2−y^2}\)-wave superconductivity of infinite-layer nickelates. *Phys. Rev. B* **101**, 060504 (2020).

12. Sakakibara, H. et al. Model construction and a possibility of cupratelike pairing in a new \(d^{9}\) nickelate superconductor (Nd,Sr)NiO\(_2\). *Phys. Rev. Lett.* **125**, 077003 (2020).

13. Lechermann, F. Late transition metal oxides with infinite-layer structure: nickelates versus cuprates. *Phys. Rev. B* **101**, 081110 (2020).

14. Werner, P. & Hoshino, S. Nickelate superconductors: multiorbital nature and spin freezing. *Phys. Rev. B* **101**, 041104 (2020).

15. Wan, X., Ivanov, V., Resta, G., Leonov, I. & Savrasov, S. Y. Exchange interactions and sensitivity of the Ni two-hole spin state to Hund’s coupling in doped \(\text{NdNiO}_2\). *Phys. Rev. B* **103**, 075123 (2021).

16. Stewart, G. R. Superconductivity in iron compounds. *Rev. Mod. Phys.* **83**, 1589–1652 (2011).

17. Caspary, R. et al. Unusual ground-state properties of UPd\(_2\)Al\(_3\): implications for the coexistence of heavy-fermion superconductivity and local-moment antiferromagnetism. *Phys. Rev. Lett.* **71**, 2146–2149 (1993).

18. Tallon, J. L., Bernhard, C. & Niedermayer, C. Muon spin relaxation studies of superconducting cuprates. *Supercond. Sci. Technol.* **10**, A38 (1997).

19. Anisimov, V. I., Bukhvalov, D. & Rice, T. M. Electronic structure of possible nickelate analogs to the cuprates. *Phys. Rev. B* **59**, 7901–7906 (1999).

20. Lee, K. W. & Pickett, W. E. Infinite-layer \(\text{LaNiO}_2\): Ni\(^{2+}\) is not Cu\(^{2+}\). *Phys. Rev. B* **70**, 165109 (2004).

21. Zhang, F. C. & Rice, T. M. Effective Hamiltonian for the superconducting Cu oxides. *Phys. Rev. B* **37**, 3759–3761 (1988).

22. Hepting, M. et al. Electronic structure of the parent compound of superconducting infinite-layer nickelates. *Nat. Mater.* **19**, 381–385 (2020).

23. Goodge, B. H. et al. Doping evolution of the Mott–Hubbard landscape in infinite-layer nickelates. *Proc. Natl Acad. Sci. USA* **118**, e2007683118 (2021).

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Methods

The nickelate thin films capped with SrTiO3 were deposited on SrTiO3 substrate by pulsed laser deposition as the respective perovskite phase before being topotactically reduced by a soft chemical process as described in section A of the Supplementary Information and elsewhere. Low-energy \( \mu \)SR was carried out at the LEM facility at the \( \mu \)E4 beamline of the Swiss Muon Source at PSI. The sample mosaic was mounted on a nickel-coated plate to achieve a flat background asymmetry. All the \( \mu \)SR data were analysed using musrfit. The ZF and wTF spectra were fit from 0.07 to 9 \( \mu \)s. To estimate the effective magnetic volume fraction of fully magnetic nickelate layers (dashed lines, Fig. 3d–g), reduced asymmetry due to muonium formation in the SrTiO3 was taken into account. The energy-dependent models were generated from a MATLAB routine.

Data availability

All \( \mu \)SR data are available in the following permanent repositories: [https://doi.org/10.16907/493c5efc-c6a8-45a7-a12f-27b6c87bd54](https://doi.org/10.16907/493c5efc-c6a8-45a7-a12f-27b6c87bd54) and [https://doi.org/10.16907/d36143e7-5bd8-465b-860b-9a3680d0a18f](https://doi.org/10.16907/d36143e7-5bd8-465b-860b-9a3680d0a18f). Histograms are also available together with the fitting software, on [http://musruser.psi.ch](http://musruser.psi.ch). A run number directory is provided in section B of the Supplementary Information. Source data are provided with this paper.

References

36. Lee, K. et al. Aspects of the synthesis of thin film superconducting infinite-layer nickelates. *APL Mater.* 8, 041107 (2020).
37. Prokscha, T. et al. The new \( \mu \)E4 beam at PSI: a hybrid-type large acceptance channel for the generation of a high intensity surface-muon beam. *Nucl.Instrum.Methods Phys. Res. A* 595, 317–331 (2008).
38. Saadaoui, H. et al. Zero-field spin depolarization of low-energy muons in ferromagnetic nickel and silver metal. *Phys. Proc.* 30, 164–167 (2012).
39. Suter, A. & Wojek, B. M. Musrfit: a free platform-independent framework for \( \mu \)SR data analysis. *Phys. Proc.* 30, 69–73 (2012).
40. Salman, Z. et al. Direct spectroscopic observation of a shallow hydrogenlike donor state in insulating SrTiO3. *Phys. Rev. Lett.* 113, 156801 (2014).
41. Simões, A. F. et al. Muon implantation experiments in films: obtaining depth-resolved information. *Rev. Sci. Instrum.* 91, 023906 (2020).

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Author contributions

J.F. and D.L. prepared and characterised the samples with support from M.O., B.Y.W., K.L. and Y.L. J.F., M.H. and A.S. carried out the \( \mu \)SR measurements with support from Z.S. and T.P. J.F. and A.S. analysed the data. M.M.M. provided the model for the energy-dependent data. J.F., M.H., J.-M.T., H.Y.H. and A.S. wrote the manuscript with input from all authors.

Competing interests

The authors declare no competing interests.

Additional information

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