Emergence of Fermi arcs due to magnetic splitting in an antiferromagnet

The Fermi surface plays an important role in controlling the electronic, transport and thermodynamic properties of materials. As the Fermi surface consists of closed contours in the momentum space for well-defined energy bands, disconnected sections known as Fermi arcs can be signatures of unusual electronic states, such as a pseudogap. Another way to obtain Fermi arcs is to break either the time-reversal symmetry or the inversion symmetry of a three-dimensional Dirac semimetal, which results in formation of pairs of Weyl nodes that have opposite chirality, and their projections are connected by Fermi arcs at the bulk boundary. Here, we present experimental evidence that pairs of hole- and electron-like Fermi arcs emerge below the Neel temperature ($T_N$) in the antiferromagnetic state of cubic NdBi due to a new magnetic splitting effect. The observed magnetic splitting is unusual, as it creates bands of opposing curvature, which change with temperature and follow the antiferromagnetic order parameter. This is different from previous theoretically considered and experimentally reported cases of magnetic splitting, such as traditional Zeeman and Rashba, in which the curvature of the bands is preserved.

Emergence of surface states in the AFM state

The measured Fermi surface in the paramagnetic (PM) state is shown in Fig. 2a, and the dispersion along selected cuts is shown in panels Fig. 2b, c. This is in good agreement with bulk band structure calculations (Fig. 1b, c). There are very broad areas of intensity in the proximity of the $E_F$ (Fermi level), consistent with the mainly three-dimensional (3D) character of the bulk bands. The lack of sharp features indicates that there is no significant presence of surface states near $E_F$ in the paramagnetic state.

On cooling below $T_N$, a long-range AFM order develops and new, very sharp features appear near $E_F$ that are consistent with the emergence of surface states, as seen in Fig. 2d–f. A new set of electron pockets appears, one residing within the bulk electron pocket and the other near the corners of the bulk hole pockets. Even more notably, four new, very sharp, disconnected contours appear around the centre of the zone. It should be noted that these features appear only in the AFM state and are not even a hint of their intensity in those parts of the momentum space above $T_N$. These features are induced by the presence of long-range AFM order and are not artefacts of the sharpening due to the enhancement of quasi-particle lifetime. The spectral intensity...
of these features appears only below $T_N$ and increases on cooling. In fact, as discussed below, the band splitting and weight of these features follow order-parameter-like temperature dependencies below $T_N$. The Fermi surface and band structure are fully fourfold rotationally symmetric, and the apparent broadening of the arcs located along the horizontal direction is due to larger data bins in this direction. These new, sharp features are indeed surface states, as their dispersion does not change with photon energy, as shown in Extended Data Figs. 2 and 3. We note that these surface states are not trivial results of band backfolding, because there are no pre-existing surface states in the paramagnetic state. It is also difficult to explain their appearance as a result of hybridization of backfolded bulk bands, as discussed in the Absence of significant band backfolding section in the Methods.

**Structure of Fermi arcs**

We examine the structure of the Fermi arcs by plotting the detailed dispersion along several cuts in the momentum space in Fig. 3. The band that gives rise to the Fermi arc shows a sharp dispersion over a relatively wide energy range close to the symmetry direction that crosses the centre of the zone shown in Fig. 3b. As we move away from the symmetry direction, the energy range over which this band has sharp intensity decreases and becomes limited to a few tens of meV near the tips of the arcs. Beyond the tips of the arc (Fig. 3b, no. 4) the sharp surface-state intensity vanishes and only very broad 3D bulk band intensity is present (Fig. 3b, no. 5 and no. 6). Although graphically the arcs may appear similar to those of cuprates, the situation is completely different. In cuprates the band giving rise to the Fermi surface is present at all temperatures and the pseudogap suppresses the spectral weight of the band only near the Fermi energy ($E_F$), while leaving the higher binding energy portion unaffected, which is clearly not the case in NdBi.

To verify the intrinsic nature of the Fermi arcs discussed above, we need to exclude the possibility that a portion of the Fermi surface is suppressed by polarization selection rules and matrix elements. We do this by performing measurements on the same cleaved surface after rotating the sample by 45°. The Fermi arcs are still present in the data thus obtained and at the same locations as before, as shown in Fig. 3c. Detailed cuts provide further evidence that the band that gives rise to Fermi arcs merges with bulk bands, as shown in Fig. 3d. These data also reveal that there is a relationship between the Fermi arc band and the surface-state electron pockets that exist below $T_N$, as they appear to disperse together.

The surface states reported here show a complex dichroic response, as shown in Fig. 3e–h, which is consistent with the presence of spin textures. The hole-like and electron-like bands have opposite dichroic responses across the mirror plane, which cannot be explained by a trivial geometric effect. In 45° geometry, the sign of the dichroic signal changes within the same band at momenta away from the experimental mirror plane (indicated by arrows in Fig. 3h). This is consistent with the presence of spin textures (spin momentum locking) and the spin complementary character of these surface states, as previously demonstrated for the case of the topological insulator Bi$_2$Se$_3$ (ref. 32). More detailed polarization studies of these states are shown in Extended Data Fig. 4.

**Band repulsion magnetic splitting**

Perhaps the most notable aspect of the surface states described above is their formation below $T_N$ and their temperature evolution. To illustrate this, in Fig. 4a we plot the Fermi surface, and in Fig. 4b the band dispersion, along selected cuts for several temperatures below and above $T_N$. The data at 30 K and 25 K reveal only broad 3D bands and the surface states are completely absent. At 24 K, a hint of intensity appears in the band dispersion (indicated by the red arrow). At 23 K, there is a clearly visible Fermi arc in the Fermi surface (FS) plot and slightly broader linear dispersion. At 20 K, this Fermi arc splits into two, with each band having opposing curvature. The dispersion data reveal splitting of the initial surface-state band into hole-like and electron-like bands. Their intensity vanishes away from the center of the Brillouin zone ($F$), which forms the Fermi arcs. At 14 K the separation between the...
two bands increases, mostly as a result of the upward movement of the electron-like band and rapid change in its curvature. At the same time its intensity near \( E_F \) increases and the electron-like Fermi arc transforms into an electron pocket, the area of which decreases with temperature (see two bottom panels of Fig. 4a).

We quantify the temperature evolution of the surface states by plotting the energy distribution curves (EDCs) at a momentum near the bottom of the electron band, as indicated by a dashed line in the bottom panel of Fig. 4b. Above \( T_N \), the EDC is a linear intensity that is cut off by the Fermi function as a result of the projection of bulk bands. Just below \( T_N \), a small peak appears at approximately 70 meV. The intensity of this peak increases on cooling, and at a few degrees below \( T_N \) it splits into two peaks. The peak closer to \( E_F \) is due to an electron-like band and the other peak is due to a hole-like band. On further cooling, the ‘hole’ peak remains mostly at the same energy of approximately 85 meV (marked by a dotted line in Fig. 4c), although increasing in intensity. The electron peak moves closer to \( E_F \) and resides at approximately 38 meV at 5.5 K. In Fig. 4d we plot the area of both peaks after subtracting and normalizing by the EDC above \( T_N \). In Fig. 4e we plot the energy separation between the EDC peaks as a function of temperature. In both cases these quantities behave in a manner similar to the AFM order parameter. The temperature dependence along vertical cuts, verification of the effect of temperature cycling and surface ageing results are shown in Extended Data Figs. 5 and 6.

We would like to emphasize the unusual nature of the magnetic splitting that we report here. In the normal Zeeman interaction, such as in an itinerant ferromagnet, the presence of an internal magnetic field splits degenerate bands into spin minority and spin majoriy bands and rigidly shifts them up and down in energy, as illustrated on the left side of Fig. 4f. In the Rashba interaction, the spin momentum locking causes the degenerate band to split in a way that makes opposite spin partners appear rigidly shifted along the momentum axis, as illustrated on the right side of Fig. 4f. In the case reported here, a linearly dispersing surface state that appears just below \( T_N \) is split into two bands with opposed curvature: electron-like and hole-like, as illustrated in Fig. 4g. On cooling, and thus increase of the internal magnetic field, the hole band remains mostly unchanged whereas the curvature of the electron band increases as it moves to lower binding energies (Fig. 4g). This behaviour is incompatible with known cases of magnetic splitting.

**Discussion**

The opposite band curvature of two bands and the sign-changing pattern of the dichroic response indicate that the surface states are massive Dirac fermions. Therefore, a possible scenario is that the surface spectrum features topological surface states. In this scenario, there are massless surface Dirac points protected by, in particular, \( C_2 \) symmetry
in the paramagnetic state, in which $C_2$ is the $180^\circ$ rotation around the surface normal direction, but they are masked because their spectra overlap with the bulk spectrum. A pair of split electron-like and hole-like bands is then generated by the gap opening of each Dirac point as a result of $C_2$ breaking below $T_N$. However, this does not explain how the gap opening enhances the spectral weight on the surface. More importantly, density functional theory (DFT) calculations do not corroborate this scenario. Other ideas, such as floating bands due to broken non-symmorphic time-reversal symmetry on the surface, are not supported by DFT calculations either. It is unlikely that the effects we observed are a result of trivial AFM band folding. In Extended Data Fig. 7 we plot, schematically, two possible scenarios of band folding. In both cases, the new surface states that we observe are located outside the overlap between normal and folded bands. Furthermore, in Extended Data Fig. 8, we show that there is no detectable signal as a result of band folding. In Extended Data Fig. 9, we compare the actual data with a simulation that assumes modest 10% band folding. Clearly, such a signal is not detected.

In fact, our DFT calculations do not reproduce the experimentally observed band structure with the reported A-type AFM (AFMA)\textsuperscript{28,29}, implying that any simple attempts based on band theory will fail. In Extended Data Fig. 10, we present the band structure and Fermi surfaces for AFMA (shown also in Fig. 1a) and also AFMC (intralayer checkerboard with out-of-plane moment) orders. No sign of surface states is found at the Fermi level for AFMA around the zone centre. Although surface states that are absent in the non-magnetic state emerge for AFMC at 150 meV below $E_F$, the overall band structure looks very different from the experimental data because AFMC clearly breaks $C_4$ symmetry.

**Fig. 3** Dispersion of Fermi arc bands. a, Fermi surface map near Γ in AFM state at $T = 6$ K. b, Band dispersion along cuts marked by dashed arrows in a. c, Fermi surface map near Γ in AFM state at $T = 6$ K after rotating the sample by 45°. d, Band dispersion along cuts marked by arrows in c. e, ARPES data measured with linear polarization along cut no. 3 marked in Fig. 1a. f, Dichroic signal (difference between ARPES intensities measured with LCP and RCP) along the same cut as in e. g, ARPES data measured with linear polarization along cut no. 5 marked in c, but spanning the whole range of $k'_x$ momenta. h, Dichroic signal along the same cut as in g.
Although the mismatch between our experiment and DFT calculations implies that the correlation effect can play an important role, we do not observe any indication of the Kondo effect, which further underpins the puzzling nature of the observed surface states. Our observations suggest the existence of surface-resonant states in the continuum of bulk states, forming disconnected arcs at the Fermi level. However, the robustness of the surface resonance against the hybridization with the bulk bands is yet to be explained.

In any case, it is evident that magnetism and spin–orbit coupling are very important. As such, the delicate interplay with magnetism, spin–orbit coupling and potential topology underlying the emergence of the Fermi arcs should provide a fascinating theory impetus, in which all symmetries and specific processes need to be taken into account. Because the surface states we observe are intimately linked to the AFM order, they can probably be controlled by the application of magnetic fields as well as temperature pulses, such as those present in ultra-fast laser pulses, thereby opening up new avenues for terahertz spintronics.

### Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-022-04412-x.

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We note that for the related compound YSb, the bulk band dispersion compared shapes of the dispersions obtained by fitting energy distribution to the corresponding dispersion plots. To show this precisely, we compared changes can be seen in the shape of the Fermi surface pockets, nor in and a cut in the direction orthogonal to it for each photon energy. No–Near the Fermi surfaces plots, we show one cut along the $\Gamma$–$M$ direction, and maps 4–8 were taken of the synchrotron-based ARPES measurements were 0.1° and 10 meV, down to sample temperatures of 8 K. The angular and energy resolutions were detected with a Scienta R4000 analyser at the RGBL-2 end station, consisting of a Scienta DA30 electron analyser, picosecond Ti:Sapphire oscillator and fourth-harmonic generator. Data from the laser-based ARPES were collected with 6.7 eV photon energy. Angular resolution was set at 2 meV. The VUV laser beam was set to vertical polarization, along the direction of the analyser slit, respectively, and the energy resolution was set at approximately 0.1° and 1°, along and perpendicular to the mirror plane, as is shown in Extended Data Fig. 4f. This is consistent with the presence of opposite spin textures in hole and electron surface states, as demonstrated previously. We contrast this behaviour with the dichroism signal measured above the mirror plane and shown in Extended Data Fig. 1b. We can confirm that the hole and electron surface states reported in this work have opposite dichroic responses, in which the sign of the circular dichroism signal for the two bands changes across the experimental mirror plane in an opposing way. This is illustrated in Extended Data Fig. 4d, e. In addition, on sample rotation by 45°, the sign of the dichroic signal changes within the same band at momenta away from the mirror plane, as is shown in Extended Data Fig. 4f. This is consistent with the presence of opposite spin textures in hole and electron surface states, as demonstrated previously. We contrast this behaviour with the dichroism signal measured above $T_N$ in the PM state and shown in Extended Data Fig. 4i, j, where such effects are not observed.

The beam with left circular (LCP), right circular (RCP), linear horizontal ( LH) or linear vertical (LV) polarization was produced using a zero-order tuneable phase retardation plate from Alphalas. The tilt of the plate was adjusted using a calibration curve and full circular polarization was verified using an external polarimeter. The location of the beam at the sample position was recorded for different polarizations using a phosphorescent plate, and movement of the beam during switching of polarization was corrected using a beam deflector within half of the beam size.
In addition, these data show that ageing effects are weak, and the surface states can survive for a long time during an experiment. At least, this is true for the experimental conditions of our laser ARPES set-up. Another example of a long experiment is presented in Extended Data Fig. 5c. Both datasets in Extended Data Fig. 5b, c show that ageing effects (primarily band broadening) can become noticeable during a long experiment, but, even after 24 h, all bands are clearly visible.

**Synchrotron data**

Data measured using higher photon energy at the synchrotron are shown in Extended Data Fig. 6. The Fermi surface map reveals the same features as when measured with the VUV laser: surface-state Fermi arcs and electron pockets that are present only below $T_s$. Sample ageing was more severe at the synchrotron due to the worse ultra-high vacuum conditions. This causes a downward shift of the $E_F$, indicating removal of electrons from the sample, which is probably due to condensation of CO. These effects were mostly absent when performing measurements in the laboratory using a laser source, as described in the previous section.

**Absence of significant band backfolding**

The long-range AFM order doubles the size of the real space unit cell, and therefore introduces a magnetic zone boundary within the BZ. The small periodic potential creates shadow bands, which are weak mirror copies of the bands about the magnetic zone boundaries (MZB). The magnetic ordering in NdBi is of AFM type, which consists of planes that have the same orientation of magnetic moments and which are stacked in AFM fashion along one axis.

If the AFM ordering vector is along the direction perpendicular to the sample surface, that is, along the (001) direction, then the MZB are horizontal planes (as illustrated in Extended Data Fig. 7b). In such cases, the top and bottom electron pockets are backfolded onto hole pockets at Gamma and vice versa. As there are no states near $E_F$ that would be backfolded onto areas where we observe the surface states, such a scenario cannot be responsible for their emergence.

A more interesting case happens when the AFM ordering vector is parallel to the sample surface. Then there could be a potential overlap between the central hole pocket and shadow bands of the electron pockets in the general area where surface states appear. This is schematically illustrated in Extended Data Fig. 7c. Even here, the surface states that we observe exist outside the areas of overlap between hole and electron shadow bands, as indicated by the blue arrows; therefore, they cannot be a result of hybridization due to band backfolding.

We also demonstrate that the backfolding effects of the bulk bands are very weak in this material and below our detection limit. In Extended Data Fig. 8 we plot the data along cuts that are equally spaced on the left and right side of the MZB. The backfolding in the AFM state should produce shadow bands, and features from the right side should appear in data on the left side, and vice versa. We note that the bulk electron band from the right PM cut (top right of Extended Data Fig. 8b) should appear with diminished intensity as shadow bands overlap the PM data on the left cut (top left of Extended Data Fig. 8b). The actual data in the AFM state on the left side does not show any such intensity existing below the surface electron band. We illustrate this in more detail by plotting MDCs at $E_F$ and ~40 meV in Extended Data Fig. 8c, d. The bulk electron pocket produces strong shoulders marked by dashed lines. In the presence of strong band folding those shoulders should appear in the AFM MDCs from the left side of the MZB. Magnified data show that such shoulders are absent down to noise level, which puts an upper limit on the intensity of shadow bands of at most 3%. This makes band backfolding very unlikely to be responsible for the emergence of the surface-state Fermi arcs that have an intensity comparable to the intensity of PM bulk bands.

We illustrate difficulties with explaining the emergence of surface states in the AFM state using the backfolding scenario by simulating its effects and comparing with actual data in Extended Data Fig. 9. In the top two panels we plot the data in the PM state along the same cuts on the left and right side of the MZB, as in Extended Data Fig. 9b. In Extended Data Fig. 9c we plot data from panel a, after adding 10% of intensity from panel b to simulate 10% shadow band intensity. The result has clearly visible features, indicated by an arrow, that are missing from actual data in the AFM state shown in Extended Data Fig. 9d. The surface-state electron pocket present in the AFM state is not only much more intense, but also located at a different binding energy than the potential shadow band.

**DFT band structure calculations**

For the bulk band structure of non-magnetic NdBi calculated in Fig. 1, we used the Perdew–Burke–Ernzerhof exchange-correlation functional in DFT, including the spin–orbit coupling (SOC) with the 4f orbitals treated as core electrons, as implemented in the Vienna ab initio simulation package. The experimental lattice constant of 6.41 Å, a $\Gamma$-centred Monkhorst–Pack (13×13×13) $k$-point mesh with a Gaussian smearing of 0.05 eV and a kinetic energy of 183 eV have been used. The DFT calculation for non-magnetic NdBi gives a band inversion around three $X$ points and the associated topological surface states for a strong topological insulator, which are similar to those features in LaBi. However, ARPES data show the absence of such surface states in the paramagnetic NdBi above $T_s$.

To try to understand the exotic magnetic Fermi arcs and surface states observed by ARPES in NdBi below $T_s$, we carried out surface band structure calculations of different magnetic configurations on the basis of DFT, as shown in Extended Data Fig. 10. However, so far, none of them can explain the observed magnetic Fermi arc. First, for the paramagnetic or non-magnetic state above $T_s$, the NdBi (001) surface spectral function in Extended Data Fig. 10a shows the band inversion along $\Gamma - M$ as projected from the avoided crossing with $p$-band inversion in the $\Gamma - X$ direction of the bulk BZ. Such band inversion makes the non-magnetic NdBi a strong topological insulator with the topological index of $Z_2 = (1;000)$, which is typical for non-magnetic early rare earth (R) bismuth 1:1 compounds in the same rock salt structure. Because two bulk X points with the band inversion are projected on the same $\mathbf{M}$ point, two surface Dirac cones overlap and are gaped to form an upper and lower surface band crossing at the $\mathbf{M}$ point, which also agrees with earlier studies on paramagnetic RbBi systems. For the 2D Fermi surface at $E_F$ in Extended Data Fig. 10d, in comparison to the bulk-only Fermi surface in Fig. 1c, the surface states around the $\mathbf{M}$ point connect and merge with the bulk electron pocket along the $\Gamma - \mathbf{M}$ direction. At lower energy $E_F - 0.15$ eV (Extended Data Fig. 10g), these surface states form an envelope around the shrinking bulk electron pocket.

For the antiferromagnetic configuration below $T_s$ we used the $\Gamma$-type AFM stacked along (001) with moment also along (001), as reported in the early neutron study by Nereson and Arnold. Our DFT+U+SOC calculation (on-site repulsion parameter Hubbard-like $U = 6.3$ eV and $J=0.7$ eV for the strongly localized Nd 4f orbitals) $U=6.3$ eV and $J=0.7$ eV gives a spin moment of 2.7$\mu_B$ and an orbital moment of 5.8$\mu_B$ in the opposite direction, resulting in a total magnetic moment of 3.1$\mu_B$ on Nd, which agrees with the experimental value of (3.1 ± 0.2)$\mu_B$. Although time-reversal symmetry is broken, non-symmetric time-reversal symmetry exists and, when combined with inversion symmetry, the bulk bands still have double degeneracy. The calculated topological index is $Z_2 = 2$ and there is also a bulk Dirac point at $E_F + 0.4$ eV that is projected at the $\mathbf{M}$ point. For surface states, as shown in Extended Data Fig. 10b, the empty Nd 4$d$ bands are 0.5 eV above the $E_F$. The band inversion along $\Gamma - \mathbf{M}$ still holds, but the two surface band crossings at the $\mathbf{M}$ point are both gaped out. In contrast to the hole Fermi arc and two surface electron pockets in the ARPES data in Fig. 2e, calculations shown in Extended Data Fig. 10b from the calculated AFMA show no surface states extending beyond the band inversion region along the $\Gamma - \mathbf{M}$ direction towards the $\mathbf{M}$ point and merging into the bulk band projections. The 2D Fermi surfaces of AFMA at the different energies in Extended Data
Fig. 10e, f are similar to those in the non-magnetic case and do not match that of the ARPES data in Fig. 2d because they are clearly missing the hole Fermi arc and the surface electron pocket on the Γ point side.

To evaluate the band-folding effect, we also considered the intralayer AFMC configuration with moment along (001), as shown in Extended Data Fig. 10c, f, i. For AFMC, the (001) surface BZ, as drawn in Extended Data Fig. 10e, is rotated by 45° and folded in reference to that of non-magnetic and AFMA. As shown in Extended Data Fig. 10c, the band inversion along the original Γ−M′ is folded at the half-point and on top of the new Γ point. The surface states of the overlapped Dirac cones at the original Γ point are folded on top and centred at the Γ point. However, the surface states and the 2D Fermi surface at different energies in Extended Data Fig. 10f, i do not match the surface hole Fermi arc and the two surface electron pockets in ARPES that appear along the Γ−M non-magnetic and AFMA. As shown in Extended Data Fig. 10f, the band inversion along the original Γ−M′ is folded at the half-point and on top of the new Γ point. The surface states of the overlapped Dirac cones at the original Γ point are folded on top and centred at the Γ point. The surface states are folded directly on top of the bulk hole pocket centred at the Γ point. Also, notably, the C3 rotational symmetry is broken because the stacking of the checkerboard AFM needs an in-plane non-symmorphic translation.

Data availability
The raw data for this work are available at the Materials Data Facility: https://doi.org/10.18126/P9B8-E7MS.

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Author contributions
B.S., P.C.C. and A.K. conceived and designed the experiment. Y.K. and A.F. performed analysis of ARPES data. J.A. and R.-J.S. provided theoretical analysis and interpretation. B.K., S.L.B. and P.C.C. grew and characterized the samples. L.-L.W. performed DFT calculations. B.S., Y.K., E.O’L., K.L., A.E., A.F., R.L., V.V., O.J.C., J.S.-B. and A.K. performed ARPES measurements and support. The manuscript was drafted by J.A., B.S., R.-J.S., P.C.C. and A.K. All authors discussed and commented on the manuscript.

Competing interests
The authors declare no competing interests.

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Extended Data Fig. 1 | Basic sample characterization. a, Derivatives of resistivity and magnetization ($d\rho/dT$ and $d(M(T)/H)/dT$) plotted as a function of temperature. b, Powder X-ray diffraction pattern for NdBi. Blue vertical lines show the expected Bragg peak positions, agreeing well with the observed pattern. Green asterisks show impurity peaks coming from Bi flux. hkl indices are assigned comparing with the reported structure.
Extended Data Fig. 2 | Photon energy-dependent data.

a, Fermi surface maps in the AFM state measured using light with different photon energy are shown in the left column. 

b, Corresponding dispersions along directions depicted by the horizontal and the vertical line on the map are shown in the central and the right columns, respectively.

c, The shape of the dispersion in Γ-X direction obtained by EDC fitting. Bullets and crosses represent results obtained from two different cleaves.
Extended Data Fig. 3 | ARPES data from NdBi in AFM and PM states measured using 21.2 eV photons. a, Data measured along Γ - X direction in the AFM state at T=10 K. b, Data measured along Γ - X direction in the PM state at T=30 K. c, Momentum Distribution Curves (MDC) plotted at E_F from data in panels a, b.
Extended Data Fig. 4 | Circular dichroism and polarization dependence.

a, Plot of portion of Fermi surface in the area where surface states are present measured using linearly polarized light b, and c, ARPES data along cut marked in panel (a) measured in the AFM and PM state respectively (sum of spectra measured using left and right circular polarization). d, dichroic signal from FS as in panel (a) e, and f, dichroic signal in AFM and PM state along same cuts as in (b) and (c) (difference of spectra measured using left and right circular polarization). g, and h, ARPES data along cut #5 marked Fig. 3c in 45 deg. sample orientation in the AFM and PM state respectively. i, and j, dichroic signal in AFM and PM state along same cuts as in (g) and (h). k, large area Fermi surface map. l, and m, ARPES spectra along cut marked with line #1 in (k) measured using linear horizontal and linear vertical polarized light, respectively. n and o, ARPES spectra along cut marked with line #2 in (k) measured using linear horizontal and linear vertical polarized light, respectively.
Extended Data Fig. 5 | Reproducibility and ageing data. 

**a**, Fermi surface maps measured from eight different samples in the AFM state. 
**b**, Spectra measured along the direction shown with a dashed line in the plot a #2 at different temperatures. A number of hours represents the time after cleave when a spectrum was measured.  
**c**, Two Fermi surface maps and two spectra measured from another sample at different times after cleave: from 6 to 24 hours. The spectra were measured in along direction shown with a dashed line in the map.
Extended Data Fig. 6 | Synchrotron data. a, Fermi surface map measured using 23eV light at T=8K. b, Spectrum measured throw the surface electron-like pocket on another sample one hour after its cleaving. c, The same spectrum measured 5 hours later.
Extended Data Fig. 7 | Schematic illustration of various band backfolding scenarios. 

a, schematic plot of 2D projected bulk FS based on calculations from Fig. 1c. 

b, 3D bulk FS and 2D projection when magnetic ordering vector is perpendicular to sample surface.

c, same as b, but for magnetic order parallel to the sample surface. Blue arrows point to parts of the surface states that exist outside the areas where bulk electron shadow band overlaps with bulk hole pocket.
Extended Data Fig. 8 | Absence of observable signal from bulk shadow bands. 

**a**, FS plot in AFM state. Green dashed line marks MZB for in-plane magnetic ordering vector. 

**b**, data along cuts on left and right side, equally distanced from MZB in PM state (top row) and AFM state (bottom row). 

**c**, MDC from cuts in panel b at E_F. Dashed lines mark strong shoulders from bulk electron pocket on right side of MZB. Insets show magnified data at momenta where bulk electron shoulders due to shadow bands are expected. 

**d**, MDC from cuts in panel b at E=-40 meV. Dashed lines mark strong shoulders from bulk electron pocket on right side of MZB. Insets show magnified data at momenta where bulk electron shoulders due to shadow bands are expected.
Extended Data Fig. 9 | Simulation of shadow intensity for in-plane backfolding. a, Data along the cut on the left side of MZB (marked in Extended Data Fig. 8a). b, Data along the cut on the right side of MZB (marked in Extended Data Fig. 8a). c, Sum of data in panel a and 10% of intensity from panel b simulating 10% backfolding in AFM state. d, Actual data along the same cut as in panel a in AFM state.
Extended Data Fig. 10 | DFT calculations. **a**, spectral functions of NdBi (001) surface in paramagnetic (non-magnetic - NM) configuration. **b**, spectral functions of NdBi (001) surface for A-type antiferromagnetic (AFMA) configuration stacked along (001) with moment also along (001). **c**, spectral functions of NdBi (001) surface for intralayer checkerboard AFM (AFMC) with moment along (001). **d–f**, the 2D Fermi surfaces at the constant energy of $E_F$ for the three magnetic configurations NM, AFMA and AFMC, respectively. **g–i**, the 2D Fermi surfaces at the constant energy of $E_F - 0.15$ eV for the three magnetic configurations NM, AFMA and AFMC, respectively. The surface Brillouin zone of AFMC is rotated by 45 degree and folded from that of NM and AFMA.