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ARTICLE OPEN

Unidirectional Kondo scattering in layered NbS₂

Edoardo Martino¹, Carsten Putzke², Markus König³, Philip J. W. Moll², Helmuth Berger¹, David LeBoeuf⁴, Maxime Leroux⁴, Cyril Proust⁴, Ana Akrap⁵, Holm Kirmse⁶, Christoph Koch⁶, ShengNan Zhang^{1,7}, QuanSheng Wu^{1,7}, Oleg V. Zazyev^{1,7}, László Forró^{1,8} and Konstantin Semeniuk¹

Crystalline defects can modify quantum interactions in solids, causing unintuitive, even favourable, properties such as quantum Hall effect or superconducting vortex pinning. Here we present another example of this notion—an unexpected unidirectional Kondo scattering in single crystals of 2H-NbS₂. This manifests as a pronounced low-temperature enhancement in the out-of-plane resistivity and thermopower below 40 K, hidden for the in-plane charge transport. The anomaly can be suppressed by the *c*-axis-oriented magnetic field, but is unaffected by field applied along the planes. The magnetic moments originate from layers of 1T-NbS₂, which inevitably form during the growth, undergoing a charge-density-wave reconstruction with each superlattice cell (David-star-shaped cluster of Nb atoms) hosting a localised spin. Our results demonstrate the unique and highly anisotropic response of a spontaneously formed Kondo-lattice heterostructure, intercalated in a layered conductor.

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INTRODUCTION

Layered van der Waals materials, such as transition metal dichalcogenides (TMDs), have attracted major interest, thanks to their rich variety of ground states and the possibility of their exfoliation down to an atomically thin level, which remarkably modifies their electronic properties^{1,2}. Recent observations of intriguing physics in artificially assembled heterostructures highlight the importance of interlayer interactions. Examples include the outstanding stability of interlayer excitons in semiconducting TMDs³, and strongly correlated states in twisted bilayer systems⁴. Relevant aspects of the inter-plane coupling can be deduced by probing out-of-plane charge transport, even in bulk materials⁵. However, enforcing the current flow strictly along the *c* axis can be rather challenging due to the crystals' common flake-like appearance and their propensity for delamination. Such a pitfall can distort the measurement results by orders of magnitude, as demonstrated in our recent study of microstructured samples of 1T-TaS₂ with a well-defined current flow⁶. This observation motivates a careful re-examination of the out-of-plane charge transport properties in this class of materials by adopting the latest state-of-the-art for quantum matter microfabrication⁷.

Here we present data on the out-of-plane electrical resistivity of bulk monocrystalline 2H-NbS₂. This material is one of the three known structural variants of layered NbS₂. The two other polytypes are 3R and 1T, the latter occurring only in atomically thin form^{8,9}. As illustrated in Fig. 1a, 1T-NbS₂ consists of corner-sharing octahedral NbS₆ cells. Layers of 2H- and 3R-NbS₂ (Fig. 1b, c) both contain NbS₆ units of trigonal prismatic geometry, but exhibit different stacking configurations. The 1T polytype has been attracting interest recently as a candidate for realising a two-dimensional magnetic system^{10,11}. 2H-NbS₂ has been actively featured in the literature due to a superconductivity below 6 K, proposed to have a multiband character. It also does not show any

charge-density-wave (CDW) order, which is uncommon for metallic TMDs^{12–17}. Another distinguishing feature of 2H-NbS₂ is its non-trivial synthesis procedure. This polytype is thermodynamically stable in a relatively narrow range of temperatures and reactant stoichiometries^{18–20}. Crystals formed during high-temperature growth must be rapidly quenched in order to capture 2H-NbS₂ in a metastable room-temperature state. However, X-ray diffraction studies have shown that the resultant material has up to 18% of pairs of neighbouring layers stacked in a 3R-like manner^{21,22}. Additionally, diffuse X-ray scattering experiments²² revealed weak traces of the $\sqrt{13} \times \sqrt{13}$ CDW reconstruction, which appears as a triangular superlattice of David-star-shaped clusters defined by 13 Nb atoms²³. Such a reconstruction is not expected for pure 2H-NbS₂ or 3R-NbS₂. Earlier theoretical investigations have predicted 1T-NbS₂ to be particularly prone to developing such a CDW order^{10,11}. One can therefore conclude that single crystals of 2H-NbS₂ contain rare, atomically thin inclusions of the 1T polytype.

Our study of 2H-NbS₂ revealed a remarkably strong low-temperature anomaly in the compound's out-of-plane resistivity (ρ_c), manifesting as a minimum at around 40 K, followed by a pronounced upturn upon further cooling. The feature is simultaneously invisible in the in-plane resistivity (ρ_{ab}), and shows a highly anisotropic response to magnetic field. Neither 2H-NbSe₂ nor 3R-NbS₂ display such an anomaly, implying that the phenomenon is linked to the structural defects specific to 2H-NbS₂. 1T-NbS₂, layers of which are one of such defects, were predicted to form a lattice of unpaired localised spins located at the centre of each David-star CDW superlattice cluster^{10,11}. We argue that planes of magnetic moments, hosted by the inclusions of 1T-NbS₂, cause a Kondo effect observable only when the current flows across these planes.

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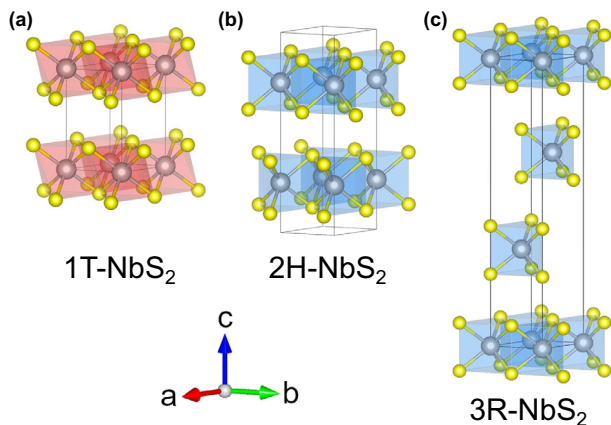


Fig. 1 Polytypes of NbS₂. Crystalline lattices of 1T-NbS₂ (a), 2H-NbS₂ (b) and 3R-NbS₂ (c). The corresponding 1-, 2- and 3-layer unit cells are marked with black wireframes. The compass shows the directions of the principal axes for all three structures. 2H-NbS₂ and 3R-NbS₂ share the same structure in the *a*–*b* plane, but have different stacking of layers along the *c* axis. For 3R-NbS₂, only one Nb atom with 6 nearest S atoms are shown for the middle two layers, for a clearer illustration of the stacking. Images produced with VESTA⁵⁷.

RESULTS

Resistivity anisotropy

Optimisation of sample geometry with focused ion beam (FIB) micro-milling greatly improves charge transport study precision^{6,7}. Using this approach, we shaped single crystals into samples with well-defined, few micron-thick and -wide current channels, oriented along the two principal directions: normal and parallel to the atomic planes (Fig. 2a shows a sample of 2H-NbS₂ produced this way). Such a design allowed simultaneous measurement of both ρ_{ab} and ρ_c via the four-point technique. Probing ρ_c on two segments of different surface-to-volume resulted in mutually consistent values, allowing us to ensure that our results were not distorted by the presence of surface-related effects or macroscopic defects.

Figure 2b shows the plots of ρ_{ab} and ρ_c of 2H-NbS₂ against temperature (*T*), as well as their ratio in the inset. Note that in contrast to the earlier study which reports an anisotropy of the order of 1000 (ref. ²⁴), our measured value was as low as 10 at room temperature, monotonically increasing to 180 on cooling. As it was shown for the case of 1T-TaS₂ using finite element simulations⁶, such an overestimate by the previous study could be a result of a non-optimised measurement geometry and an incorrect prior assumption that the anisotropy is very large. While ρ_{ab} has a conventional metallic temperature dependence, ρ_c is also metallic, but shows a few noteworthy features. First, the residual out-of-plane resistivity is very high, presumably due to a significant concentration of static defects. Second, ρ_c approaches saturation in the high-temperature region. This flattening of resistivity may be attributed to the mean free paths decreasing to the point of becoming comparable to the interlayer separation, a concept known as the Mott-Ioffe-Regel limit²⁵. Third, at low temperatures, ρ_c displays a minimum at around 40 K, with a major upturn at lower temperatures. No corresponding feature exists in ρ_{ab} (in agreement with the previous results²⁶). All studied samples of 2H-NbS₂ showed qualitatively identical behaviour, with slight differences in the absolute values of resistivity—related to slight impurity content variations—and temperatures of the minimum distributed in the 30–40 K range.

We compared ρ_c of 2H-NbS₂ to that of the isostructural and isovalent compound 2H-NbSe₂ (dashed line in Fig. 2b). The latter material did not exhibit a similar low-temperature anomaly. Based on the nominal lattice parameters, density functional theory calculations predict that the two compounds will have nearly

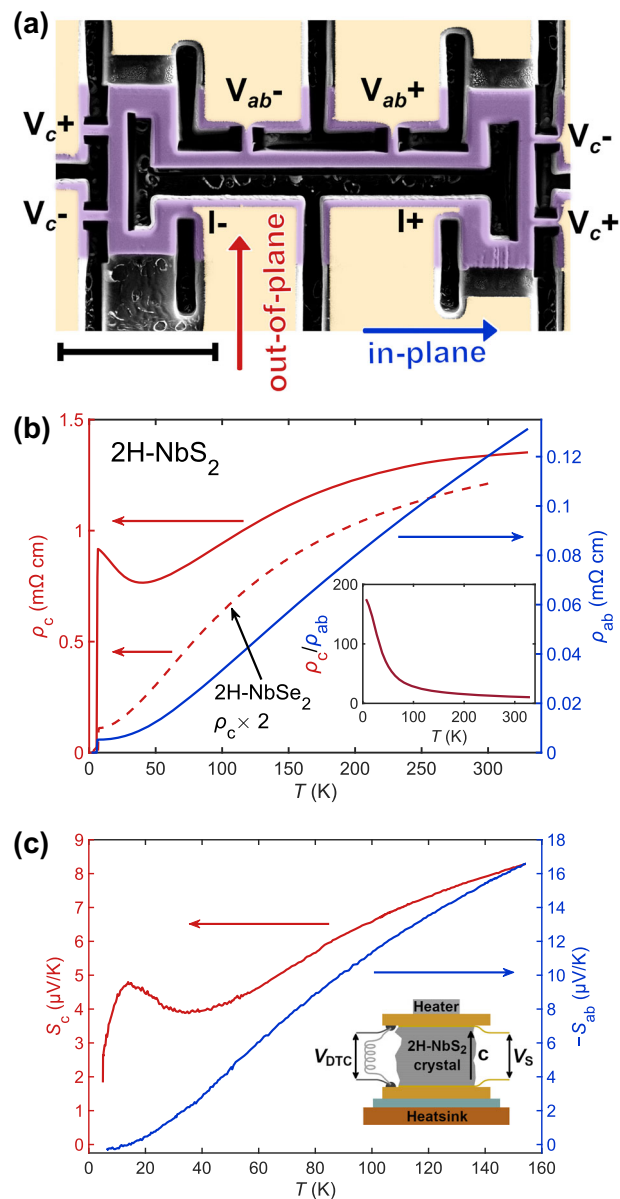


Fig. 2 Interlayer charge dynamics in 2H-NbS₂. **a** Scanning electron microscope image of a 2H-NbS₂ sample, structured with focused ion beam for accurate resistivity anisotropy measurements. False colouring is used: purple – crystal, beige – gold film. The scale bar in the bottom left is 20 μm long. The current sourcing (I) and voltage probing (V) electrodes are labelled. **b** Plots of the in-plane (ρ_{ab} , blue) and out-of-plane (ρ_c , red) resistivities of 2H-NbS₂ against temperature (*T*). The dashed red line stands for the out-of-plane resistivity of 2H-NbSe₂, scaled by a factor of 2. Resistivity anisotropy of 2H-NbS₂ is plotted in the inset. **c** Seebeck coefficients of 2H-NbS₂ for the out-of-plane (S_c) and in-plane (S_{ab}) directions as functions of temperature, measured on bulk single crystals (note that S_{ab} is negative). The setup for measuring S_c is illustrated schematically. The crystal was approximately 1 mm long in the *c* axis direction (indicated in the drawing), and 2–3 mm long laterally. The value of S_c is the ratio of the voltage across the sample (V_s) and the thermal gradient across it, determined from the differential thermocouple voltage (V_{DTC}). The sample sat between two copper plates, which homogenised temperature at its two faces and was electrically decoupled from the heatsink by a thin sapphire plate.

identical electronic band structures (see Supplementary Note 1 and Supplementary Figs. 1 and 2). We therefore conclude that the upturn of ρ_c of 2H-NbS₂ is not intrinsic to the nominal structure of the compound, but is caused by crystalline lattice defects.

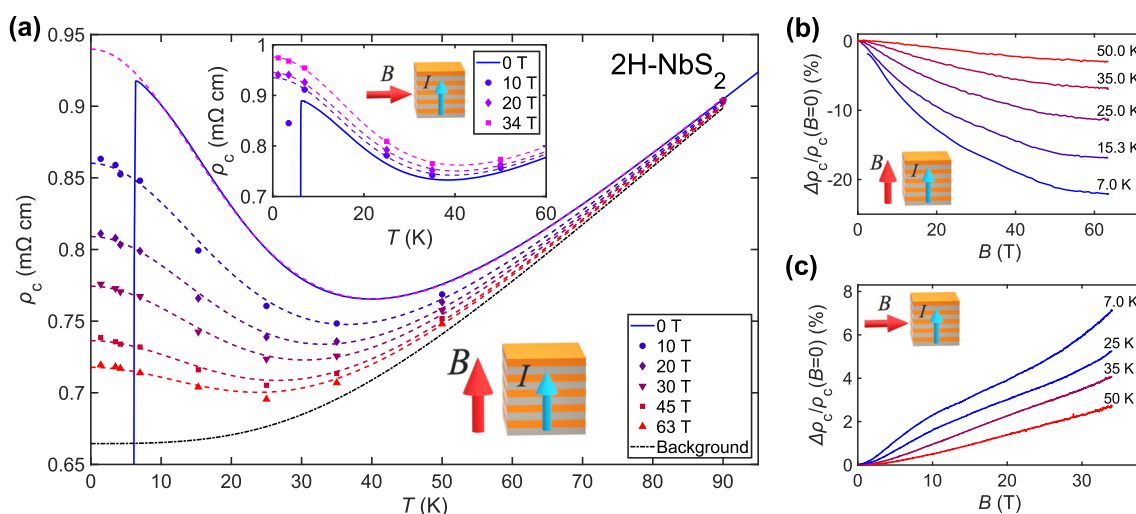


Fig. 3 Out-of-plane magnetotransport in 2H-NbS₂. **a** Out-of-plane resistivity (ρ_c) as a function of temperature (T) for various longitudinal (main plot) and transverse (inset) magnetic fields (B). Solid lines and markers represent the measured data. Dashed lines in the main plot are fits according to the numerical renormalisation group theory of Kondo effect. The fitted model includes a field-independent contribution due to the residual temperature-independent resistance as well as the electron–phonon scattering, described by the Bloch–Grüneisen formula (dash-dot line). Dashed lines in the inset are guides for the eye. The two datasets were collected using different samples, which explains the slight resistivity mismatch for zero field. **b**, **c** Relative changes in ρ_c under out-of-plane (**b**) and in-plane (**c**) magnetic fields.

Seebeck coefficient anisotropy

The Seebeck coefficient (S) is a useful quantity for sensitively probing energy landscape variations near Fermi level. The open-circuit voltage generated by the thermal gradient is unaffected by the presence of static defects such as vacancies or non-magnetic stacking faults. On the other hand, the Seebeck coefficient is a function of the energy dependence of the conduction electron scattering rate. This is then strongly affected by the occurrence of resonance peaks in the density of states close to the chemical potential. Seebeck coefficient of 2H-NbS₂ revealed a prominent peak at approximately 15 K, appearing only for the out-of-plane thermal gradient (Fig. 2c). The phonon drag phenomenon produces a similar feature in the temperature dependence. However, it manifests only in conductors with long phonon and charge carrier mean free paths—such as semimetals or extremely pure metals—where momentum-conserving scattering is dominant²⁷. This is highly unlikely for 2H-NbS₂, as its high content of static defects should clearly favour momentum-relaxing scattering. Furthermore, absence of the corresponding S_{ab} peak rules out the phonon drag from the possible S_c anomaly origins. An alternative interpretation of the peak, the Kondo effect, will be discussed further below.

High-field magnetotransport

The out-of-plane resistivity anomaly of 2H-NbS₂ demonstrated a particularly curious response to magnetic fields. As can be seen in Fig. 3a, the transverse and longitudinal out-of-plane magnetoresistances of the material are strikingly different. Applying the field along the c axis suppresses the resistivity upturn, shifting the minimum to lower temperature. Yet even at 63 T the anomaly is still present. Consequently, at 50 K and below, ρ_c decreases when magnetic field is increased, with signs of saturation appearing around 50 T (Fig. 3b). In contrast, in transverse magnetic field, ρ_c behaves as a more typical orbital magnetoresistance, common to metals. It is positive, and about three times weaker in magnitude than the longitudinal one (Fig. 3c) without significantly affecting the shape of the upturn in $\rho_c(T)$.

In order to emphasise the observed phenomenon’s highly anisotropic nature, we also report the in-plane magnetotransport of 2H-NbS₂ up to 14 T. The magnetoresistance is weak for all field directions, as can be seen in Fig. 4a, but similarly to ρ_c , ρ_{ab} is also

reduced by the field along the c axis (clearly depicted in Fig. 4b), which could be a trace of the same anomaly. The in-plane field-dependence of ρ_{ab} (Fig. 4c) is likely governed by orbital effects, like in the case of ρ_c .

DISCUSSION

The question of the origin of the anomalies of ρ_c in 2H-NbS₂ will now be addressed. A number of phenomena could result in a finite-temperature resistivity minimum in a metal. Resistivity upturns can be caused by electron–electron interactions in the presence of static disorder^{28–30}. However, the corresponding quantum mechanical correction is either weakly enhanced by a magnetic field, or is effectively field-independent. A closely linked phenomenon of weak localisation (WL) is also known to produce an additional contribution to resistivity at low temperatures³¹. In this scenario, when a series of scattering events cause an electron to follow a closed path, quantum interference favours the net backward scattering over the forward one. Magnetic flux threading these scattering loops shifts the phases of the wave functions, diminishing the effect. In our case, when electrons are scattered between different planes, the closed paths should have comparable projections along the in-plane and out-of-plane directions. However, the upturn is only influenced by the c -axis-oriented field, contradicting the WL-based interpretation. A metal–insulator transition or conduction based on a thermally activated hopping between defects³² would cause a divergence of ρ_c at the lowest temperatures, which was not the case. The possibility of quantum tunnelling playing a significant role is ruled out based on a linear relation between current and voltage (Supplementary Note 2 and Supplementary Fig. 3). Resistivity upturns have also been observed in strongly doped cuprate superconductors^{33,34}. In those materials, the effect is believed to be caused by scattering from magnetic droplets forming around non-magnetic impurities. This interpretation, however, relies on the existence of strong electronic correlations, and therefore does not apply to our system.

Finite-temperature resistivity minimum in a metal is also a well-known signature of the Kondo effect, a scattering of conduction electrons of dilute localised magnetic moments³⁵. Besides the upturn, the characteristic features of the phenomenon, observable in charge transport, include a negative curvature of $\rho_c(T)$ at the

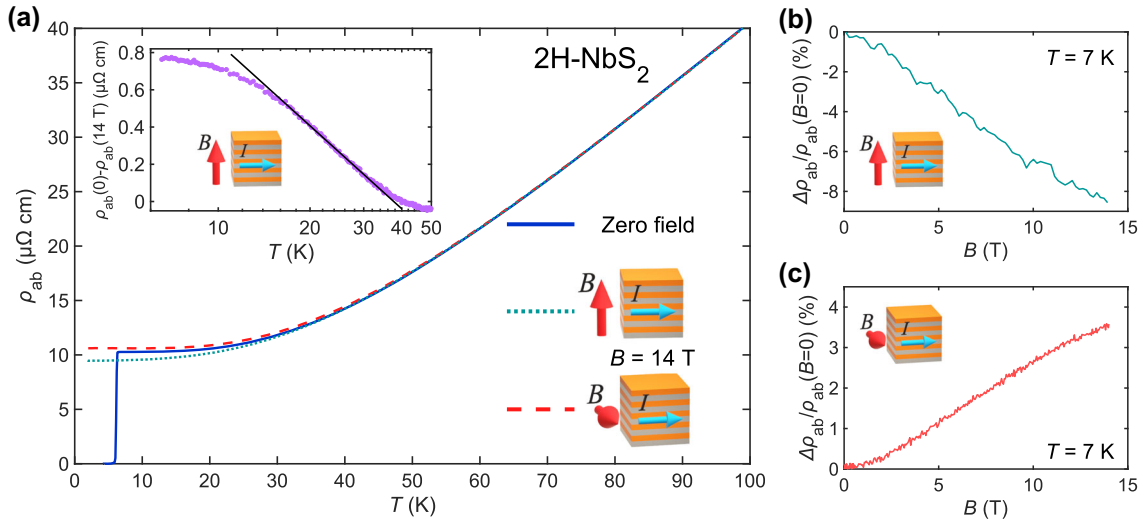


Fig. 4 In-plane magnetotransport in 2H-NbS₂. **a** In-plane resistivity (ρ_{ab}) as a function of temperature (T) at zero and 14 T magnetic field (B). The change of ρ_{ab} between zero field and 14 T (out-of-plane field) is plotted in the inset on a logarithmic T scale. The black line in the inset corresponds to the logarithmic temperature dependence. **b, c** In-plane magnetoresistance for the out-of-plane (**b**) and in-plane (**c**) field.

lowest temperatures and a suppression of the upturn by magnetic field, which causes spin-flip scattering to become inelastic^{36,37}. The observed peak in the Seebeck coefficient is also characteristic to dilute and concentrated spin systems, including Kondo lattices^{38,39}. It originates from the resonant scattering in the Kondo channel at the Fermi level. Above the Kondo temperature, T_K , the resonance is smeared out, and depending on the specifics of a system, the peak in S appears at a temperature between 0.3 and $0.9 T_K$ (refs. ^{39,40}). When temperature is low enough, the localised spins are screened and the excitations obey simple power laws, like those of a Fermi liquid. For example, S varies as T/T_K for $T/T_K < 0.1$ – 0.15 for several typical Kondo alloys in the dilute, single impurity limit⁴¹.

Measurements of ρ_c under high pressure, presented in Supplementary Note 3 and Supplementary Fig. 4, show that the upturn remains extremely robust up to the highest achieved pressure of 1.9 GPa. Applying the pressure weakly shifts the minimum of ρ_c up in temperature. This is consistent with the behaviour expected from Kondo systems^{42,43}.

We therefore argue that scattering of magnetic impurities is the most fitting explanation of our observations. The temperature dependence of ρ_c in 2H-NbS₂ is consistent with the one expected from the numerical renormalisation group (NRG) theory calculations for Kondo effect^{36,44}, as illustrated by the fit in Fig. 3a. We modelled ρ_c with a sum of three contributions: a temperature-independent residual resistivity ρ_0 , an electron–phonon scattering term ρ_{e-p} (captured by the Bloch–Grüneisen formula) and the Kondo term ρ_K (the only magnetic-field-dependent term), for which we used the common empirical expression closely following the results of the NRG theory^{36,44}:

$$\rho_K(T) = \rho_{K0} \left(1 + \left(2^{1/a} - 1 \right) (T/T_K)^2 \right)^{-a}. \quad (1)$$

The fitting procedure is described in more detail in Supplementary Note 4, with the help of Supplementary Figs. 5 and 6 and Supplementary Table 1.

This explanation immediately raises a question regarding the nature of our system’s magnetic impurities. The standard scenario where magnetic atoms are uniformly distributed clearly does not fit our picture. Doping 2H-NbS₂ with Fe results in the upturn observable in ρ_{ab} as well as the disappearance of superconductivity⁴⁵. Additionally, the undoped material does not display a corresponding signature in the heat capacity⁴⁶. Lack of pronounced anomaly effects on ρ_{ab} implies that the

responsible defects take the form of sparse planes, extending along the layers. When the current then flows along the layers, only a small fraction of the conduction electrons move in close proximity to these planes. But for the out-of-plane current flow, effectively all charge carriers have to pass through them, resulting in a particularly strong influence. Although we observed planar irregularities in the crystalline lattice via transmission electron microscopy, their atomic structure could not be determined due to a limited resolution (see Supplementary Note 5 and Supplementary Figs. 7 and 8). Taking a closer look at the in-plane magnetoresistance for the c -axis-oriented field reveals that the difference between ρ_{ab} at 0 and 14 T increases linearly with respect to $\ln(T)$ between 30 and 15 K (Fig. 4a inset), which further supports our hypothesis. This means that a minute contribution of Kondo scattering is present in ρ_{ab} , but it is not strong enough to change the sign of the gradient of $\rho_{ab}(T)$.

The presence of 1T-NbS₂ layers, evidenced by the characteristic CDW signatures²², offers a fascinating interpretation of our findings, illustrated in Fig. 5. As we mentioned in the introduction, the $\sqrt{13} \times \sqrt{13}$ CDW order, associated with the 1T polytype, forms a triangular superlattice of David-star-shaped clusters defined by 13 Nb atoms²³. The electronic structure of monolayer 1T-NbS₂ as well as 1T-NbSe₂ in such a configuration has been predicted to contain one very flat band around the Fermi level. This makes the materials susceptible to electronic instabilities like Mott localisation, with a concomitant magnetic order^{10,47,48}. The referenced works found the ferromagnetic insulating state as the most stable, although others have proposed that such triangular lattices can host antiferromagnetic spin-liquid phases^{49,50}. These magnetic planes play the role of scatterers in the Kondo effect, however, their concentration appears to be too low for a detection via magnetometry measurements. The described scenario is conceptually similar to the Kondo effect occurring in artificially fabricated magnetic tunnel junctions^{51,52}, yet in our case the phenomenon is observed in a spontaneously formed system. The same kind of Kondo interaction has been very recently observed in scanning tunnelling spectroscopy studies of the 2H/1T or 1H/1T heterostructures of NbSe₂ (ref. ⁵³), TaS₂ (ref. ⁵⁴) and TaSe₂ (ref. ⁵⁵), grown by molecular beam epitaxy. One outstanding question is the anomaly’s markedly different response to the two orientations of magnetic field. This difference is probably coming from the localised electron’s highly anisotropic g -factor, causing a very small spin splitting (less than T_K),

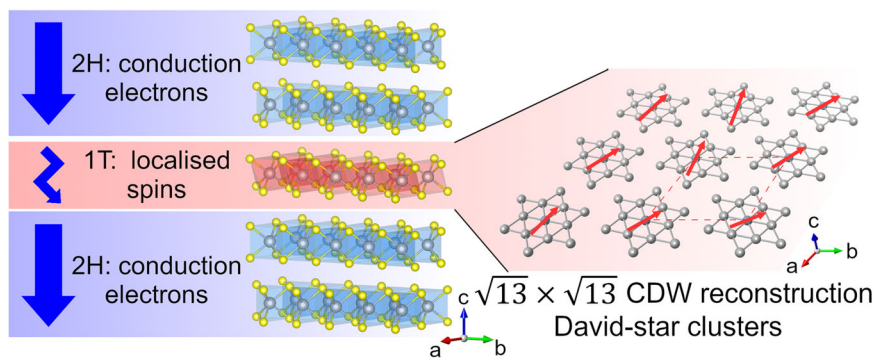


Fig. 5 **1T-NbS₂ inclusions in 2H-NbS₂.** Schematic visualisation of the proposed interpretation of the observed out-of-plane charge transport anomaly. The 2H-NbS₂ crystal (structure in the centre) contains inclusion layers of 1T-NbS₂ (highlighted in red). 1T-NbS₂ undergoes a $\sqrt{13} \times \sqrt{13}$ charge-density-wave (CDW) reconstruction. The Nb atoms in the CDW state are arranged into David-star-shaped clusters, superlattice of which is depicted on the right (only Nb atoms are shown, the dashed line marks the unit cell after the reconstruction). Each cluster contains an unpaired localised spin at the centre (red arrows on the right). The orientations of spins in the illustration are arbitrary and are not meant to suggest any particular ordering. This array of localised magnetic moments causes the itinerant electrons in the 2H-NbS₂ bulk to experience Kondo scattering during the out-of-plane current flow (blue arrows).

but could also be related to the magnetic ordering. Sizeable anisotropy of the g -factor is expected for systems with strong spin-orbit coupling, such as TMDs⁵⁰.

Since 2H-NbS₂ is known to contain frequent 3R-like stacking faults, it is natural to ask whether the anomaly is somehow caused by the inclusions of 3R-NbS₂. We measured the latter compound's out-of-plane resistivity, and while the corresponding temperature dependence was surprisingly found to be non-metallic, the extremely weak reaction of the interlayer conduction to the longitudinal magnetic field ($\Delta\rho_c/\rho_c \approx 0.1\%$ at 14 T) was incompatible with the behaviour observed in 2H-NbS₂ (see Supplementary Note 6 as well as Supplementary Fig. 9 for the relevant data on 3R-NbS₂). The abundance of these stacking faults could explain the high residual component of ρ_c . The current understanding is that the poor conductivity of 3R-NbS₂ is not intrinsic, but rather originates from the disorder due to self-intercalated Nb atoms⁵⁶. However, in 2H-NbS₂, the abundance of stacking faults results in high residual component of ρ_c and good in-plane metallicity.

In summary, we have demonstrated that a delicate alternation of the interlayer crystalline structure of 2H-NbS₂, by introducing different polymorphs of the same atomic composition, dramatically affects the material's physical properties. In particular, the crystal's 2H stacking is occasionally disrupted by the 1T layers, which undergo a CDW instability. This then results in a triangular superlattice of David-star-shaped clusters, each hosting a lone spin at the centre. Such a texture of localised magnetic moments can be seen as a two-dimensional Kondo lattice, immersed into the metallic bulk of the 2H polytype. When the electric field or thermal gradient are then applied along the c axis, electronic transport shows a pronounced Kondo effect manifesting as anomalies in the out-of-plane resistivity and Seebeck coefficient. But when they are applied within the plane, there is no sign of spin-dependent scattering. The observation of this highly anisotropic phenomenon occurring in a naturally formed heterostructure has been made possible, thanks to the careful tailoring of the crystal by FIB. Our work therefore shows the importance of adopting new experimental techniques in studying novel electronic materials, especially highly anisotropic Van der Waals structures.

METHODS

Focused ion beam microfabrication

Microstructured samples were extracted from monocrystalline flakes of TMDs. The starting crystals had the lateral size of the order of 1 mm and

were at least 100 μm thick. After identifying a clean region on a crystal's surface, free of cracks or buckling, a rectangular lamella was defined by milling away the surrounding material using an FEI Helios G4 Xe plasma FIB microscope. The typical dimensions of a lamella were around $120 \mu\text{m} \times 60 \mu\text{m} \times 5 \mu\text{m}$ (with up to 20% variations in lengths between different samples), with the intermediate dimension corresponding to the extent along the c axis of a crystal. The milling current for this stage was 60 nA, with 30 kV column voltage. An FEI Helios G3 Ga FIB microscope was then used for polishing the surface of the lamella with a 1 nA beam in order to ensure the parallelism of the two largest faces. After extraction, the lamella was glued to a sapphire substrate with a tiny amount of Araldite Rapid epoxy, keeping the external face exposed. Besides anchoring the lamella, the epoxy also formed a meniscus around it that smoothly connected the substrate's surface to the lamella's exposed face. The setup was then sputter coated with a 100 nm layer of gold. Next, the Ga FIB milling at 10 nA was used for defining the probing electrodes by selectively removing the sputtered gold layer, and for patterning the lamella in order to form the current channel and voltage probing points. The procedure was concluded with polishing the exposed side faces of the sample with a 1 nA ion beam in order to clean the surface of the re-deposited material and define the final dimensions of the device. Since the entire bottom face of the sample was rigidly attached to the substrate, differential thermal contraction and compressibility were expected to produce inhomogeneous stresses throughout the lamella. In our study, these stresses did not have a significant influence on the measured data. More detailed information about the FIB-assisted sample preparation can be found in the relevant review paper⁷ and references therein.

Resistivity measurements

Resistivity was measured via the four-point technique with direct or alternating excitation currents in the 20–40 μA range. Temperature sweeps' rate was limited to 1 K/min for the ambient pressure and of 0.5 K/min for the high-pressure measurements in order to reduce the thermal lag and gradients.

Resistivity at high pressure was measured using a piston cylinder cell produced by C&T Factory. Daphne oil 7474 was used as a pressure-transmitting medium. Pressure was determined from the changes in resistance and superconducting transition temperature of a sample of Pb located next to the 2H-NbS₂ sample.

Measurements in high magnetic fields were conducted at the high magnetic field facilities in Grenoble (up to 34 T DC field) and Toulouse (up to 63 T pulsed field). Quantum Design PPMS was used for measurements in fields up to 14 T.

Seebeck coefficient measurements

Seebeck coefficient was measured using an in-house setup. For the in-plane Seebeck coefficient measurement, a thin and long sample was mounted on a ceramic bar. One end of the bar was connected to the thermal bath, while the other one had a resistive heater attached. A differential thermocouple was used to measure the temperature difference

across the sample. The out-of-plane Seebeck coefficient measurement was performed using a setup displayed in Fig. 2c and described in the corresponding caption.

DATA AVAILABILITY

The data that support the findings of this study are available from the authors (K.S., E.M., and L.F.) upon reasonable request. Data used for generating the plots can be found at <https://doi.org/10.6084/m9.figshare.16720621>.

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AUTHOR CONTRIBUTIONS

E.M. and K.S. prepared and conducted resistivity and Seebeck coefficient measurements and wrote the manuscript together with L.F. C.P., M.K. and P.M. assisted with the FIB fabrication process. H.B. synthesised the crystals used in the study. D.L. assisted with resistivity measurements at the high DC magnetic field facility in Grenoble. M.L. and C.P. conducted resistivity measurements at the pulsed magnetic field facility in Toulouse. A.A. secured the magnet time for the experiments in Toulouse. H.K. and C.K. conducted the TEM study. S.Z., Q.W. and O.Y. provided theoretical support and the DFT data. L.F. is the project leader.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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