Enhanced Superconductivity in Monolayer $T_d$-MoTe$_2$ with Tilted Ising Spin Texture

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Crystalline two-dimensional (2D) superconductors with low carrier density are an exciting new class of materials in which superconductivity coexists with strong interactions, the effects of complex topology are not obscured by disorder, and electronic properties can be strongly tuned by electrostatic gating. Very recently, two such materials, 'magic-angle' twisted bilayer graphene and monolayer $T_d$-WTe$_2$, have been reported to show superconductivity at temper-
atures near 1 K. Here we report superconductivity in semimetallic monolayer $T_d$-MoTe$_2$. The critical temperature $T_c$ reaches 8 K, a sixty-fold enhancement as compared to the bulk. This anomalous increase in $T_c$ is only observed in monolayers, and may be indicative of electronically mediated pairing. Reflecting the low carrier density, the critical temperature, magnetic field, and current density are all tunable by an applied gate voltage, revealing a superconducting dome that extends across both hole and electron pockets. The temperature dependence of the in-plane upper critical field is distinct from that of 2$H$ transition metal dichalcogenides (TMDs), consistent with a tilted spin texture as predicted by ab initio theory.

The 2D limit of superconductivity has been extensively studied in metal or metal-oxide films, which suffer from disorder and typically reside in the dirty limit, i.e. $\xi_0 >> l$ where $\xi_0$ is the coherence length and $l$ is the electronic mean free path. In contrast, exfoliated 2D superconductors such as NbSe$_2$ and TaS$_2$ are highly crystalline. With samples of sufficient quality, it is possible to reach the clean limit ($\xi_0 << l$), where new phenomena may emerge in applied electric and magnetic fields. For example, in NbSe$_2$ and other 2$H$-phase TMDs, spin-orbit interaction (SOC) results in a locking of the electron spin out of the plane of the crystal, resulting in an enhancement of the in-plane upper critical field, $H_{c2}^{\parallel}$, by up to $7 \times$ beyond the Pauli limit.$^1$–$^3$

2D SCs also offer an alternative way of tuning the superconducting order via electrostatic doping, which can change carrier density and screen interactions. This has recently been explored in MoS$_2$, TiSe$_2$ and other TMD semiconductors. However, the high carrier densities (i.e. $> 10^{14}$/cm$^2$) required for superconductivity necessitate the use of ionic liquid gating. Very recently, superconductivity has been induced by electrostatic doping at $n < 10^{13}$ cm$^{-2}$ in bilayer
graphene and monolayer WTe$_2$. For bilayer graphene with a small interlayer twist, superconductivity with $T_c$ up to 1.5 K occurs at small doping away from a correlated insulator phase\cite{5}, similar to high-$T_c$ superconductors. For $T_d$-WTe$_2$, the monolayer is a small-bandgap insulator with topological edge states\cite{6,9} and like twisted bilayer graphene can be tuned between insulating, metallic, and superconducting regimes, with a $T_c$ of up to 0.7 K. In this work, we explore the superconducting properties of the monolayer form of the semimetallic TMD, $T_d$-MoTe$_2$. Whereas $T_d$-WTe$_2$ has to date been studied only in the dirty limit\cite{10,11}, advances in synthesis and nanofabrication allow us to achieve the clean limit in $T_d$-MoTe$_2$. At the same time, we retain the semimetallic properties allowing for easy tunability with an electrostatic gate.

In the bulk, $T_d$-MoTe$_2$ is a type-II Weyl semimetal\cite{12} with a low carrier density\cite{13}. In order to achieve the clean limit in monolayers of this material, it is necessary to overcome two significant experimental challenges - firstly, to synthesize high quality crystals and secondly, to exfoliate and study the monolayers without destroying the crystal quality. In this study, the high quality synthesis has been achieved by using a tellurium flux assisted growth and quenching into the $T'$ phase. The resultant crystals have typical residual resistance ratios of approximately 2000, an almost two orders of magnitude improvement over recent reports\cite{13}. To overcome the second challenge of creating high quality monolayers for transport studies, thin (1, 2, and 6-layer) flakes were exfoliated inside an inert-atmosphere glove box and encapsulated between $\sim 30$ nm thick hexagonal boron nitride ($h$BN) crystals to reduce environmental disorder and provide protection from degradation in air\cite{15}. Making clean electrical contact to these monolayers without degradation presents another challenge. In this work, electrical contact was provided by metal electrodes embedded within the
hBN\textsuperscript{[15]} (see Fig. S1), and sample resistance was measured in a four-probe configuration. For a more detailed description, please refer to Methods.

The crystal structure of monolayer $T_d$-MoTe$_2$ is isostructural to that of WTe$_2$ (Fig. 1a). Previous studies have shown that bulk crystals show a transition to the $T_d$ phase upon cooling below 240 K\textsuperscript{[17]} whereas for thin samples the $T_d$ phase is stabilized to above room temperature\textsuperscript{[18]} We note that the $T'$ and $T_d$ phases differ primarily in layer stacking, and are identical for monolayers. In the absence of any external factors, the electronic bandstructure for MoTe$_2$ yields electron and hole pockets without spin splitting. By introducing an applied out-of-plane electric field, akin to a back gate voltage in our devices, inversion symmetry is broken and as a result significant spin-orbit coupling develops and splits the electron and hole pockets\textsuperscript{[19]}. For this reason, and in reasonable agreement with our data as will be discussed later, all of the properties shown in Fig. 1 are calculated under the assumption of an applied, out-of-plane electric field of 0.1 V/nm. Density functional theory (DFT) calculations predict that the monolayer is semimetallic, with $\sim 50$ meV overlap between the conduction and valence bands (Fig. 1b). There is one hole pocket at the $\Gamma$ point with a carrier density of $n = 1.2 \times 10^{13}/\text{cm}^2$ and two electron pockets ($n = 0.6 \times 10^{13}/\text{cm}^2$) at the two sides of the $\Gamma$ point, denoted as the $\pm Q$ pockets. Whereas the $\Gamma$ pocket is nearly spin degenerate, the $\pm Q$ pockets exhibit a spin-splitting of $\sim 5$ meV. Moreover, the spin texture of the $\Gamma$ pocket strongly depends on the momentum orientation, while the spin texture of the $\pm Q$ is rather independent of momentum. However, as of yet there has been no verification of this band structure through direct experimental evidence. In fact, one report indicates a potential bandgap in few-layered $T_d$-MoTe$_2$\textsuperscript{[20]}. There have been two recent angle-resolved photoemission spectroscopy
(ARPES) studies on monolayer $T_d$-MoTe$_2$: one shows semimetallic behavior with large band overlap for monolayer $T_d$-MoTe$_2$ grown on graphene$^{21}$, whereas another reports weak overlap and potentially a gap opening for exfoliated MoTe$_2$ on gold$^{22}$.

Figure 2a shows the measured resistivity of bulk and monolayer samples upon cooling (data for 2L and 6L is shown in Fig. S2). The measured bulk resistivity shows the expected $T' - T_d$ phase transition at 240 K. The $h$BN-encapsulated monolayer remains metallic down to low temperature. The monolayer, 2L and 6L samples do not show the $T' - T_d$ phase transition, consistent with previous studies$^{18}$. The metallic behavior of the monolayer rules out the presence of a bandgap, consistent with the calculated band structure. A super-linear normal state magneto-resistance (left inset) and low normal-state Hall coefficient (Fig. S3) provide further evidence that MoTe$_2$ is a nearly charge compensated semimetal. This sample shows ambipolar gate response, with a strongly decreasing resistivity with the injection of either holes or electrons, as shown in Fig. 4c below. This behavior is in qualitative agreement with theoretical and ARPES studies$^{21,22}$. However, the ability to substantially change resistance by injecting $\sim 10^{13}$ cm$^{-2}$ carriers suggests that the band overlap (and intrinsic carrier density) is smaller than indicated in Fig. 1b. We note that a second monolayer sample (S2) shows unipolar gate response and lower resistivity, consistent with static doping from crystal impurities or substrate charge (Fig. S4).

The central result of this paper is shown in Fig. 2b. Upon cooling, monolayer $T_d$-MoTe$_2$ shows a strong enhancement of superconductivity when compared to the bulk. The sample shown (S1) has a $T_c = 7.6$ K, almost two orders of magnitude larger than the bulk $T_c$ of $\sim 0.1$ K. A second sample (S2) studied below shows $T_c = 5$ K. In contrast, the 2- and 6-layer samples show no
superconducting behavior down to the lowest temperatures measured (20 mK for 6L and 250 mK for 2L). Suppression of $T_c$ in few-layered samples where interlayer coupling is weaker is consistent with the trend seen in bulk $T_d$-MoTe$_2$ under pressure, where $T_c$ increases with stronger interlayer interaction.\textsuperscript{14}

More generally, the absence of superconductivity in the 2- and 6-layer samples is not surprising, given that many factors tend to suppress superconductivity in the 2D limit. Ginzburg-Landau (GL) theory predicts suppression of superconductivity in thin films below the bulk coherence length\textsuperscript{23}, as seen in other crystalline 2D superconductors (e.g. $2H$-NbSe$_2$\textsuperscript{11} and 1UC FeSe on bilayer graphene\textsuperscript{24}). In addition, repulsive electron-electron interactions, represented by the screened Coulomb pseudopotential $\mu^*$ in Eliashberg theory, increase as materials approach the 2D limit. Increasing $\mu^*$ suppresses $T_c$ by decreasing the effective pairing interaction, given approximately as $N(0)V = \frac{\lambda - \mu^*}{1 + \lambda}$\textsuperscript{25} where $\lambda$ represents the retarded pairing interaction.

For the above reasons, enhancement of $T_c$ in the 2D limit is extremely rare, with just a few notable examples. Surfaces of metals have been shown to have enhanced $T_c$,\textsuperscript{26} although the enhancement is only a few percent. Increasing the density of states by doping is one common way that $T_c$ can be manipulated in 2D materials\textsuperscript{27}. In FeSe grown on strontium titanate (STO) $T_c$ is enhanced by an order of magnitude\textsuperscript{28}, a case where both the density of states and the pairing interactions are substantially increased in the monolayer limit\textsuperscript{29}. $2H_a$-TaS$_2$ shows increasing $T_c$ in thin samples\textsuperscript{29} with a four-fold enhancement in the monolayer.\textsuperscript{30} Potential mechanisms include an increase in the density of states via suppression of a competing charge-density wave\textsuperscript{31}, decreased interlayer coupling\textsuperscript{29}, and the formation of a second superconducting band below a critical
thickness\textsuperscript{30}. The recent examples of low-density 2D superconductors - monolayer \( T_d\)-WTe\textsubscript{2}\textsuperscript{10,11} and twisted bilayer graphene - both involve injecting carriers with an external gate. However, our Hall and gate-dependent transport measurements indicate that carrier density in monolayer \( T_d\)-MoTe\textsubscript{2} is not significantly increased in comparison to the bulk. The increase in \( T_c \) must therefore come from an increase in the pairing interaction. Such an increase does not seem to be consistent with phonon-mediated superconductivity: in van der Waals materials, the in-plane phonons do not significantly change for monolayers, and as discussed above \( \mu^* \) is expected to be largest for monolayers. There is already significant evidence in bulk that the superconductivity in \( T_d\)-MoTe\textsubscript{2} is electronically mediated\textsuperscript{32,34}. We speculate that the change in the Coulomb interaction with dimensionality is a plausible reason for the enhanced \( T_c \) via spin fluctuations, although more work is necessary to explore the mechanism of superconductivity in this material.

Next we characterize the superconducting phase diagram of sample S2 under applied magnetic fields. Figure 2c shows the resistivity in color scale as a function of temperature and applied field (\( H^\perp \)) perpendicular to the 2D plane. The solid points correspond to the boundary where the resistance reaches 90% of the normal-state value, which are used to define the upper critical field \( H^\perp_{c2} \). \( H^\perp_{c2} \) reaches a zero-temperature limit of 1.5 T, and decreases linearly with increasing T above 1K. This behavior is expected from the 2D GL equation for fields out of plane:

\[
\mu_0 H^\perp_{c2} = \frac{\Phi_0}{2\pi \xi_0^2} (1 - T/T_c),
\]

where \( \Phi_0 \) is the flux quantum, \( \mu_0 \) the permeability of free space, and \( \xi_0 \) the in-plane coherence length.\textsuperscript{35} The solid line shows a linear fit to the data above 1K, which yields \( \xi_0 = 13.9 \) nm (16 nm for \( \mu_0 H^\perp_{c2} = \frac{\Phi_0}{2\pi \xi_0^2} \) and \( H^\perp_{c2}(350 \text{mK}) \)), half the value of the bulk coherence length.\textsuperscript{33} This value is much smaller than the lower bound for the electronic mean free path, 93
nm (see Supplementary). Therefore, our monolayer $T_d$-MoTe$_2$ is far from the dirty limit, in which spin-orbit scattering (SOS) can obscure the spin texture of the Fermi surface. In a conventional 2D superconductor, $H_{c2}^\parallel$ is set by the Pauli limit, which describes the breaking of Cooper pairs by alignment of spins along the applied field. The measured upper critical field, estimated as 25 T in S2, substantially exceeds this limit ($H_p = 9.2$ T), indicating that SOC strongly enhances $H_{c2}^\parallel$.

As shown in Fig. 2d, for low fields the response follows a square root temperature dependence, altogether presenting a scenario similar to the case of NbSe$_2$\cite{11}.

Owing to the relatively low carrier density, one may vary the carrier density in MoTe$_2$ by applying a voltage to a graphite back gate underneath the hBN-encapsulated MoTe$_2$. From the thickness and dielectric constant of the hBN, we estimate that the induced carrier density is $0.5 \times 10^{12}$/cm$^2$ per applied volt. Figures 3a and 3b show the modification in the superconducting transition of sample 1 with gating. The temperature-dependent resistivity (Fig. 3a) shows a strong gate-induced modification of the superconducting transition, which broadens and decreases in temperature with increasing $V_{bg}$. Likewise, the response to applied perpendicular field ($H_{\perp}$) at 250 mK (Figure 4b) shows significant modification with $V_{bg}$. From the data in Figures 3a and 3b, we extract $T_c$ and $H_{c2}^\perp$ defined as 50% of the resistivity in the normal state, just above the superconducting transition. These are plotted, together with the normal state resistivity, as a function of $V_{bg}$ in Fig. 3c. Interestingly, whereas $T_c$ decreases uniformly with increasing $V_{bg}$, $H_{c2}$ peaks at nearly the same value of $V_{bg}$ as the maximum of resistivity. Although the maximum $T_c \sim 8K$ is observed in the hole dominated region, we still see a large $T_c$ ($\sim 5$ K) as compared to the bulk in the electron dominated region. For sample S1, $T_c$ increases as more hole carriers are injected.
leading to a concurrent decrease in the normal state resistance. Whereas in sample S2, we see the reverse behavior (see Fig. S4), a decrease in $T_c$ as the hole concentration is increased as well as a concurrent increase in the normal state resistance, suggesting S2 is over-doped with holes. Together, the electrical response of these two samples suggests the existence of a superconducting dome which relies on both the hole and electron pockets which likely peaks around $10^{14}$/cm$^2$ hole density.

Finally, to explore the relationship between superconductivity and the spin texture of the Fermi surface in more detail, we examine the response under high magnetic fields (Fig. 4). As a reference point, we first consider the case of 2D $2H$-TMDs. In general, for a 2D system, one can take into consideration the SOC vector, $g_k$, as a function of momentum. At time-reversal-invariant points such as the $\Gamma$ point, or at $k = 0$, and to leading order of momentum $g_k$ has to vanish due to its odd parity under time-reversal symmetry, i.e. $g_{-k} = -g_k$. To include SOC effects at such points we have to consider $k$-dependence at higher orders, resulting in a strongly momentum-dependent spin texture. However, at a generic non-time-reversal-invariant point ($\pm Q$ pockets), the SOC vector, to leading order, becomes a nonzero constant Zeeman field, denoted as $g$, which couples to only one component of electron spin and is independent of momentum. To recover the overall time-reversal symmetry, at the time-reversal partner $-k$, the SOC vector flips its sign and becomes $-g$. This SOC at a pair of non-time-reversal invariant points is what is known as Ising SOC$^3$, where the overall spin texture resulting from this SOC is determined by the point group symmetry. In $2H$-TMDs, such as NbSe$_2$ and TaS$_2$ the point group symmetry at the spin-split hole pockets locks the spins in the out-of-plane direction, as shown in Fig 4a. This produces an
enhanced resilience against realignment by a parallel magnetic field and thus an increased $H_{c2}^\parallel$ beyond the Pauli limit.

Unlike the $2H$-TMDs, a significantly different spin texture is expected from monolayer $T_d$-TMDs, i.e. WTe$_2$ and MoTe$_2$. From DFT calculations (Fig 1c.), $T_d$-MoTe$_2$ has an Ising SOC vector which is tilted with respect to the out-of-plane direction and has a polar angle of $\sim 45^\circ$ (shown in Fig 4b.) due to the low symmetry at the $Q$ points. With this in mind, we can choose a tilted Ising SOC vector $g = (0, g, g)$ and, given an in-plane magnetic field $H = H(\cos \phi, \sin \phi, 0)$, we can compute $\Delta_{\parallel} = g \cdot \hat{H}$ and $\Delta_{\perp} = |g \times \hat{H}|$, which both depend on the angular direction, $\phi$, of the applied magnetic field. As shown in Fig. 4c., the ratio $|\Delta_{\parallel}/\Delta_{\perp}|$ can then vary from 0 to 100%, depending on the magnetic field direction. As a result, the in-plane upper critical field will be highly anisotropic. That is, the enhancement with respect to the Pauli limit will depend strongly on $\phi$ (lower panel of Fig. 4c.).

The measured in-plane response of monolayers of both NbSe$_2$ and TaS$_2$ is shown in Fig. 4d. In agreement with prior reports, the upper critical field follows a square root temperature dependence over the entire measurable range, $H_{c2}^\parallel = H_0 (1 - T_c/T_c0)^{1/2}$. For comparison, Fig. 4e shows the measured $H_{c2}^\parallel$ versus $T$ for sample S1. A square root dependence, blue dashed line in Fig. 4e., can be fit to temperatures near $T_c$, but this dependence overestimates the upper critical field as the temperature is decreased further. To better understand the trend as $T \to 0$ K, we consider the effects of spin-orbit scattering on the superconducting behavior using the Klemm-Luther-Beasley (KLB) model (dotted magenta line, see Methods for details). This model assumes that the superconductivity is in the dirty limit (i.e. $\xi_0 >> l$) with strong spin-orbit scattering. How-
ever, the KLB model shows a similar overestimation as $T \to 0$ K and from our estimations (see Supplementary) S1 and S2 do not meet the criteria for the dirty limit. Ruling out KLB theory and the GL model as a method of understanding the behavior of $H_{c2}$, we pursue a model which takes into account the electron’s spin texture on the Fermi surface. The solid line in Figure 4e represents solutions to a linearized gap equation, similar to the case of ionic-liquid gated MoS$_2$, that takes into account SOC from both in-plane and out-of-plane polarized spins (see Supplementary). From the fitting we find a ratio of the in- to out-of-plane SOC strength, $\Delta_{so}/\Delta_{so}^\perp$, of $\sim$15% for sample S1 with $\Delta_{so}^\perp \sim 2.34$ meV, in reasonable agreement with the splitting from the DFT calculated electronic bandstructure shown in Fig. 1b. For sample S2 (Fig. 4f), we find a $\Delta_{so}/\Delta_{so}^\perp$ of $\sim$4.6% ($\Delta_{so}^\perp \sim 1.5$ meV), a third as much as in sample S1. As mentioned above, we expect $H_{c2}$ to be highly anisotropic depending on the alignment of the in-plane magnetic field with respect to the crystal axis of the sample. Therefore the difference between samples S1 and S2 is in qualitative agreement with what is expected from Fig. 4c and reaffirms the titled nature of the Ising SOC in monolayer MoTe$_2$. Other effects, such as sample quality, may also contribute to the different SOC parameters found in S1 and S2.

We note that enhancements in $H_{c2}^\parallel$ of up to $4 \times$ the Pauli limit have also been observed in monolayer WTe$_2$, suggesting some form of Ising SOC. However, at the time it remained unclear whether this enhancement could be attributed to the SOC. In previous works, monolayer WTe$_2$ has only been measured well within the dirty limit, $l \sim 5$ nm and $\xi_0 \sim 100$ nm. In this limit there can be strong spin-orbit scattering which obscures the spin texture of the Fermi surface by randomizing the spin orientation of the electrons while simultaneously enhancing $H_{c2}^\parallel$, making it
difficult to discern enhancement by SOS versus enhancement by SOC. In our work, we circumvent this problem by producing samples from high quality starting material and through clean device fabrication to achieve devices well within the clean limit, allowing us to probe the spin texture.

The telluride family of TMDs remains poorly explored and rich phenomena should emerge now that reliable and clean fabrication processes are available for the study air-sensitive monolayer films. The demonstration here of strongly enhanced, gate-tunable superconductivity in monolayer $T_d$-MoTe$_2$ should motivate significant future studies to understand both the mechanism for the observed enhancement and to confirm the proposed tilted Ising SOC. Moreover, its electronic structure is highly sensitive to external inputs like strain or electric fields\textsuperscript{19,38,39}, allowing study of how the superconducting phase can be modified by varying the SOC or inducing topological insulator states. The tunability of superconductivity by electric or displacement fields should also enable new devices such as tunable Josephson junctions.

**Methods**

**Device Assembly and Fabrication** For sample fabrication 20-30 nm thick $h$-BN flake is first exfoliated onto SiO$_2$, and holes are etched using CHF$_3$ or SF$_6$ plasma. A second, larger diameter hole is then opened through a PMMA mask and then Pd/Au, (20/50 nm) is deposited into the holes, forming an embedded contact in the $h$-BN flake that has an overlapping portion, henceforth referred to as via contact\textsuperscript{16}. This is then picked up by a dry transfer method using polypropylene carbonate (PPC) as the pickup polymer\textsuperscript{40}. Monolayer $T_d$-MoTe$_2$ flakes are exfoliated onto PDMS, identified optically, and subsequently picked up from PDMS using the already picked up via contacts. Stacks
are then placed onto a previously Ar-O$_2$ annealed\textsuperscript{[1]} 20-30 nm thick, \textit{h}-BN crystal. Except for the initial via contact method, all of the aforementioned steps were performed inside a nitrogen-filled glovebox. After encapsulation, the devices are removed from the glovebox, the PPC removed by rinsing in chloroform, and etched using O$_2$-CHF$_3$ plasma. Contacts were fabricated through conventional e-beam lithography techniques and Ti/Au, 5/75 nm, was deposited to make contact to the via contacts, with the overlapping region being larger to insure that any gap caused during the transfer process is filled, preventing exposure of the sample to air. To check quality, devices were initially cooled down to 1.6 K, then removed and stored in a glovebox until inserting into an 18 T superconducting magnet coupled with a $^3$He cryostat.

\textbf{Single Crystal Growth} High quality single crystals were prepared by combining molybdenum powder (99.999\% ) and tellurium lumps (99.9999+\%) in a ratio of 1:20 in a quartz ampoule. The ampoules were subsequently sealed under vacuum ($\sim 5 \times 10^{-6}$ Torr). The reagents were then heated to 1100 °C within 24 h and dwelled at this temperature for 24 h before being cooled to 880 °C over 400 h. At 880 °C the tellurium flux was decanted in a centrifuge and the samples was quenched in air. The subsequently obtained 1T'-MoTe$_2$ single crystals were annealed at 425 °C with a 200 °C gradient for 48 h to remove any residual tellurium. As a quality check, previous batches following this recipe have yielded bulk crystals with a residual resistivity ratio of 700 to 2000.

\textbf{Measurements} Measurements were done using the standard 4-probe technique with a Stanford Research SR830 lock-in amplifier coupled with low-pass RC filters in either a 9 T $^4$He Janis cryostat or 15 T $^3$He cryostat at Columbia University. For fields beyond 15 T, measurements were taken
at the National High Magnetic Field Laboratory in Tallahassee, Florida using the 18 T $^3$He SCM2 system or the 36 T Series-Connected Hybrid.

**Klemm-Luther-Beasley (KLB) Fitting** The KLB model is defined by a fit to $\ln T/T_c + \Psi\left(\frac{1}{2} + \frac{3\tau_{SO}^2 \mu_B^2 H^2}{4\pi \hbar k_B T}\right) - \Psi\left(\frac{1}{2}\right) = 0$, where $\Psi$ is the digamma function, $\tau_{SO}$ the spin-orbit scattering time, and $\mu_B$ is the Bohr magneton.
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Figure 1 | Crystal structure and electronic band structure of $T_d$-MoTe$_2$. a, Crystal structure of the monolayer. b, Calculated electronic band structure for an applied out-of-plane electric field of 0.1 V/nm for monolayer $T_d$-MoTe$_2$. c, Calculated Fermi surface (Top) and spin texture (Bottom), with the spin direction indicated by arrows. The two electron pockets are spin-polarized similar to the $2H$-phase materials, but with an additional tilt. In the central hole pocket, the spin within each band rotates completely, from out of plane, to in plane, to out of plane again. The bottom-most cartoon depicts the spin texture along the $k_z - k_x$ plane, highlighting the angle of the spin texture.
Figure 2 | Temperature dependent transport properties. 

**a.** Measured resistivity as a function of the temperature for the monolayer (1L) and bulk up to 300 K. Inset: Normal state magnetoresistance for monolayer MoTe$_2$ and for $T=250$ mK. Red dashed line is a linear fit to the low field data. 

**b.** Resistivity as a function of the temperature up to 9 K for monolayer, bilayer (2L), and six-layer (6L) samples. The dashed line indicates $T_c$ for bulk $T_d$-MoTe$_2$ under ambient pressure. 

**c.** Resistivity (color scale) as a function of temperature and perpendicular magnetic field. 

**d.** Resistivity as a function of temperature and field for fields parallel to the ab-plane. Solid points represent derived upper critical fields. Solid lines are fits to Ginzburg-Landau theory as discussed in the text.
Figure 3 | Gate tunability of the superconducting transition. a, Resistivity as a function of the temperature for several values of the gate voltage, $V_{bg}$ for monolayer $T_d$-MoTe$_2$ sample 1. All curves are vertically displaced by 1 kΩ for clarity. b, Resistivity as a function of the perpendicular magnetic field with varying gate voltage. c (top) Normal-state resistivity (at $H^\perp = 10$ T); (middle) measured upper critical field; (bottom) critical temperature, as a function of the gate voltage.
Figure 4  | Effects of spin-orbit coupling on superconductivity.  

**a,b** SOC representation for 2H and \( T_d \)-MoTe\(_2\) (cut along \( k_x \)), respectively.  

**c** (top panel), Calculated ratio between in- and out-of-plane SOC as a function of the in-plane azimuthal angle, \( \phi \).  

(bottom panel), Calculated enhancement of the in-plane upper critical field as a function of \( \phi \).  

**d** Measured \( H_{c2}^{\parallel} \) for fields parallel to the \( ab \)-plane for monolayer, 2H-TaS\(_2\) and 2H-NbSe\(_2\).  

Dashed lines are fits to GL theory as discussed in the text.  

**e**, \( H_{c2}^{\parallel} \) vs \( T_c \) for monolayer \( T_d \)-MoTe\(_2\) sample 1.  

The dashed cyan line is a fit to GL theory; the dotted magenta line a fit to KLB theory; and the solid black line is a fit to the theory described in the text, with the in-plane SOC being 15\% of the out-of-plane SOC.  

Notice that both GL and KLB theory overestimate \( H_{c2}^{\parallel} \) as \( T \to 0 \) K.  

**f** \( H_{c2}^{\parallel} \) as a function of \( T_c \) for monolayer MoTe\(_2\), sample 2.  

The solid blue line is a fit to the theory described in the text, with in-plane to out-of-plane SOC ratio of 4.6\%.  

Adapted from ref\([1]\) and from ref\([2]\), Nature Publishing Group (d).