Clean 2D superconductivity in a bulk van der Waals superlattice

Data repository file index

Main text data files

Figure 1: 2D superconductivity and $Ba_3Nb_5S_{13}$

Panel A: Survey of superconductors

"Fig_1a_superconductorSurvey.csv" – contains superconducting transition temperature, cleanliness ratio, and two-dimensionality ratio as defined in the main text for a variety of bulk, thin film, and exfoliated superconductors. See supplementary material for associated references.

Panel E: HRTEM image along [1-100] zone-axis

"Fig_1e_HRTEM.tiff" – Raw HRTEM image of single crystal looking along the [1-100] zone axis. Scale bar corresponds to 1 nm.

Panel F: Basic transport and magnetization data

"Fig_1f_RT.csv" – $\rho_{xx}(T)$ from 0.28 K to 300 K in units of mΩ-cm

"Fig_1f_MT_10_ZFC.csv" – ZFC susceptibility from 0.4 K to 1.2 K in CGS units

"Fig_1f_MT_10_FC.csv" – FC susceptibility from 0.4 K to 1.2 K in CGS units

Figure 2: Quantum oscillations and electronic structure of $Ba_3Nb_5S_{13}$

Panel A: High-field magnetoresistance at multiple fixed angles

"Fig_2a_MRvAng.csv" – Magnetoresistance (MR) in arbitrary units from 1 T to 31 T at angles [-8°, 2°, 12°, 22°, 32°, 42°, 47°, 52°] as measured from the *c*-axis of the crystal.

Panel B, C: Low-frequency Fast Fourier transform (FFT) of quantum oscillations

"Fig_2b_FFTAng.csv" – FFT amplitude of background subtracted magnetoresistance, arbitrary units, at fixed angles (same angles as panel A) versus *c*-axis projected frequency $F\cos\theta$ in the range 0 T to 3 kT.

Figure 3: 2D superconductivity and Pauli limit breaking in $Ba_3Nb_5S_{13}$

Panel A: High-field magnetoresistance at multiple fixed angles

"Fig_3a_IV.csv" – Temperature dependence of $I(V)$ characteristics across the superconducting transition. I and V in units of mA and μV respectively. Temperatures in dataset are, in units of Kelvin, [0.95, 0.92, 0.88, 0.86, 0.82, 0.80, 0.78, 0.71, 0.65, 0.48, 0.28].

"Fig_3a_IValpha.csv" – Exponent α of power law fit to $I(V)$ characteristics at same temperature as main panel.

Panel B: Low temperature resistivity as a function of field at multiple fixed angles.

"Fig_3b_lowCurr_A.csv", "Fig_3b_highCurr_B.csv" – Resistivity in units of μΩ cm as a function of magnetic field $\rho_{xx}(\mu_0 H)$ in the field range 0 T to 14 T collected using low and high-currents (see main text) at the angles [0°, 15°, 30°, 45°, 50°, 70°].

"Fig_3b_lowCurr_B.csv – Resistivity in units of μΩ cm as a function of magnetic field $\rho_{xx}(\mu_0 H)$ in the field range 0 T to 14 T collected using low current setting (see main text) at the angles [80°, 90°].

Panel C: Angle dependence of the upper critical field H_{c2}

"Fig_3c_Hc2.csv – Angular dependence of the upper-critical field with error bars in units of T. See main text for definition of Hc2 and error bars.

Figure 4: Superconducting phase diagram of $Ba_3Nb_5S_{13}$

Panel A: Fixed angle field-temperature phase diagrams

"Fig_4a_phaseDiagram_[ANG].csv" – Field-temperature (units of Kelvin and Tesla respectively) phase diagrams of excess conductivity (see main text for definition) measured at fixed angles ANG=[85°, 86°, 87°, 88°, 89°, 89.5°, 90°] in the temperature range [0.28 K, 1.5 K] and field range [-7 T, 7 T]. First row of data is field values and first column is temperatures.

Panel B: Enhanced stability of superconductivity for field in-plane

"Fig_4b_phaseDiagram_difference.csv" – Result of subtracting 90° phase diagram from 84° phase diagram showing region of superconductivity that appears for field applied along the in-plane direction. First row of data is field values and first column is temperatures.

Panel C: Upper-critical field versus angle

"Fig_4c_Hc2.csv" – Upper critical field as a function of angle computed from field-temperature phase diagrams for $T/T_{BKT} = 0.3$ and $T/T_{BKT} = 0.8$.

Supplementary material

Figure S1: X-ray photoelectron spectroscopy

"Fig_S1_XPS.csv" – X-ray photoelectron spectrum in the energy range [0 eV, 1100 eV] in units of counts per second (cps)

Figure S3: TEM diffraction

Panel A: TEM diffraction along 0001 zone-axis

"Fig_S3a_TEMdiffraction_0001.tiff" – Raw TEM diffraction image taken along the [0001] zone-axis. Scale bar in image corresponds to 1 nm^{-1}.

Panel B: TEM diffraction along 1-100 zone-axis

"Fig_S3b_TEMdiffraction_1-100.tiff" – Raw TEM diffraction image taken along the [1-100] zone-axis. Scale bar in image corresponds to 1 nm^{-1}.

Figure S4: TEM diffraction linescans

"Fig_S4b_linescanA.csv" , "Fig_S4b_linescanB.csv" , "Fig_S4b_linescanC.csv" – Linescans, intensity versus inverse lattice constants, along the three primary hexagonal axes in the *ab*-plane of the TEM diffraction pattern taken along the [1-100] zone-axis (see supplementary material).

Figure S5: X-ray photoelectron spectroscopy

Panel A: HRTEM 0001 zone-axis

"Fig_S5a_HRTEM_0001.tiff" – Raw HRTEM image taken along the [0001] zone-axis. Scale bar in image corresponds to 1 nm.

Panel B: HRTEM 1-100 zone-axis

"Fig_S5b_HRTEM_1-100.tiff" – Raw HRTEM image taken along the [1-100] zone-axis. Scale bar in image corresponds to 1 nm.

Figure S6: Powder x-ray diffraction

"Fig_S6_PXRD.csv" – Powder x-ray diffraction pattern in the 2θ range [10°, 70°]. Vertical axis in arbitrary units of intensity

Figure S8: Sample dependence of normal state properties

Panel A: Sample dependence of $\rho(T)$

"Fig_S8a_FL01.csv", "Fig_S8a_FL03.csv", "Fig_S8a_FL04.csv" – Resistivity (mΩ cm) as a function of temperature (Kelvin) for four samples [FL-01, FL-03, FL-04, and FL-H_{c2}]. Data for sample FL-H_{c2} same as Fig. 1F.

Panel B: Temperature dependence of FL-01 magnetoresistance

"Fig_S8b_MRvT.csv" - Field-symmetrized magnetoresistance for sample FL-01 in units of percent at fixed temperatures from 300 K to 1.8 K in the field range [-9 T, 9 T]. Temperatures included are [300 K, 150 K, 50 K, 40 K, 30 K, 20 K, 1.8 K].

Panel C: Sample dependence of magnetoresistance

"Fig_S8c_FL01-04.csv" - Field-symmetrized magnetoresistance in units of percent for seven different samples at T = 1.8 K in the field range [-9 T, 9T].

Panel D: Sample dependence of high-field magnetoresistance

"Fig_S8d_FL-HF1.csv"High-field field-symmetrized magnetoresistance in units of percent for two samples, FL-HF1 and FL-HF2. Field range [1 T, 31 T] and at T = 1.5 K.

Figure S9: Sample dependence of superconducting transition

Panel A: Sample dependence of magnetization at superconducting transition

"Fig_S9a_MT_09_ZFC.csv", "Fig_S9a_MT_09_FC.csv" - Field cooled (FC) and zero field cooled (ZFC) demagnetization corrected DC susceptibility as a function of temperature in the range [0.4 K, 1.2 K] for two samples. Sample MT-10 same as Fig. 1F. Units are CGS, $4\pi\chi$. Measured with applied field of H = 4.7 Oe applied along the *c*-axis.

Panel B: Sample dependence of resistance at superconducting transition

"Fig_S9b_FLhc2_RT.csv", "Fig_S9b_FLT1_RT.csv", "Fig_S9b_FLT2_RT.csv" - Resistance normalized to the normal state value (unitless) as a function of temperature in the range [0.28 K, 1.7 K] for three different samples, FL-Hc2, FL-T1, and FL-T2.

Figure S10: Sample dependence of $H_{c2}(\theta)$

"Fig_S10_normHc2.csv", "Fig_S10_normHc2b.csv" – Upper-critical field normalized to value at field applied along *ab*-plane H_{c2}/H_{c2}^{ab} (unitless) as a function of angle in the range [0°, 95°] for two samples.

Figure S13: High-field magnetoresistance

Panel A: Temperature dependence of high-field magnetoresistance

"Fig_S13a_MRvTemp.csv" – High-field magnetoresistance in units of ohms in the field-range [1 T, 31 T] applied along the c-axis at fixed temperatures. Temperatures included are [0.39 K, 1.0 K, 1.5 K, 10 K, 15 K, 20 K, 30 K].

Panel B: Angle-dependence of high-field magnetoresistance

Same as Fig. 2A

Figure S14: Background subtracted magnetoresistance

Panel B:

"Fig_S14b_MRvAng_bkgSubtracted.csv" - Result of background subtraction procedure (see supplementary material) for data in Fig. S13(b). First row contains (Temperature (K), Angle (deg.)). First column contains magnetic field values in units of Tesla.

Figure S15: Temperature dependence of quantum oscillation FFT spectrum

Panel A:

"Fig_S15a_fftTemp.csv", "Fig_S15a_filteredSdH_alpha.csv", "Fig_S15a_filteredSdH_beta.csv", "Fig_S15a_filteredSdH_gamma.csv" – Fast Fourier transform of magnetoresistance at various fixed temperatures and band-pass filtered SdH oscillations of the three oscillation groups (see supplementary material).

Panel B:

"Fig_S15b_alphaEffMass.csv", "Fig_S15b_betaEffMass.csv", "Fig_S15b_gammaEffMass.csv" – Oscillation amplitude (see section S6(d) of supplementary material) of three main oscillation groups.

Figure S17: Fluctuation conductivity at superconducting transition

Panel A:

"Fig_S17a_ALScaling.csv" – Aslamazov-Larkin scaling analysis of fluctuation conductivity. See Sec. S7 of supplementary material for details.

Panel B:

"Fig_S17b_ALwMakiThompsonData.csv" – Data for Aslamazov-Larkin + Maki-Thompson fluctuation conductivity model used to estimate the superconducting layer thickness.

Figure S19: Normal state low-field magnetoresistance

Panel A:

"Fig_S19a_MR_4K.csv", "Fig_S19a_MR_20K.csv", "Fig_S19a_MR_30K.csv", "Fig_S19a_MR_40K.csv" – Low-field magnetoresistance in units of percent at fixed temperatures. Temperatures include are [4 K, 20 K, 30 K, 40 K].

Panel B:

"Fig_S19b_mobilityvT.csv" – Mobility computed from low-field magnetoresistance in units of cm^2/Vs as a function temperature in Kelvin.

Figure S22: Optical and AFM imaging

Panel A:

"Fig_S22a_singleXtalImage.tiff" – Optical microscope image of typical $Ba_3Nb_5S_{13}$ single crystal.

Panel B:

"Fig_S22b_exfoliatedFlakesOptical.tiff" – Array of four optical microscope images showing typical results from scotch tape exfoliation of $Ba_3Nb_5S_{13}$ single crystal. Scale bar in all images four images is 20 microns.

Panel C:

"Fig_S22c_exfoliatedFlakeOptical_highZoom.tiff" – High magnification optical image of flake exfoliated from single crystal. Scale bar is 50 microns. Region bounded by black box examined further using AFM.

Panel D:

"Fig_S22d_exfoliatedFlakeAFM_topography.eps" – AFM topograph of flake within black bounding box of Fig. S22(c)

Panel E:

"Fig_S22e_exfoliatedFlakeAFM_linecut.eps" – Linecut taken along red line in AFM topograph shown in Fig. S22(d)

Figure S23: Normal state resistivity of 2*H*-NbS_2

Panel A:

"Fig_23a_RT_NbS2_01.csv", "Fig_23a_RT_NbS2_02.csv", "Fig_23a_RT_NbS2_03.csv" – Resistance normalized to normal state value across the superconducting transition for three bulk 2*H*-NbS_2 single crystals.

Figure S24: Resistivity anisotropy of 2*H*-NbS_2 and $Ba_3Nb_5S_{13}$

"Fig_S24_NbS2_beta.csv", "Fig_S24_BNS_corbino.csv", "Fig_S24_BNS_montgomery.csv" – Temperature dependence of resistivity anisotropy ρ_{zz}/ρ_{xx} in the temperature range [2 K, 300 K] for two samples each of 2*H*-NbS_2 and $Ba_3Nb_5S_{13}$.

Figure S25: Angular dependence of 2*H*-NbS_2 upper-critical field

"Fig_S25_NbS2_hc2.csv" – Upper-critical field (in units of Tesla) as a function of angle measured from the c-axis in the range [0°, 105°] for 2*H*-NbS_2.

Figure S26: Resistivity across the superconducting transition of 2*H*-NbS_2

"Fig_S26_RvT_NbS2_01.csv", "Fig_S26_RvT_NbS2_02.csv"- Resistivity as a function of temperature normalized to the low-temperature value in the temperature range [2 K, 300 K] for two samples each of 2*H*-NbS_2 and $Ba_3Nb_5S_{13}$ (same data as Fig. S8a).