Signatures of the topological $s^{+-}$ superconducting order parameter in the type-II Weyl semimetal $T_d$-MoTe$_2$

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In its orthorhombic $T_d$ polymorph, MoTe$_2$ is a type-II Weyl semimetal, where the Weyl fermions emerge at the boundary between electron and hole pockets. Non-saturating magnetoresistance and superconductivity were also observed in $T_d$-MoTe$_2$. Understanding the superconductivity in $T_d$-MoTe$_2$, which was proposed to be topologically non-trivial, is of eminent interest. Here, we report high-pressure muon-spin rotation experiments probing the temperature-dependent magnetic penetration depth in $T_d$-MoTe$_2$. A substantial increase of the superfluid density and a linear scaling with the superconducting critical temperature $T_c$ is observed under pressure. Moreover, the superconducting order parameter in $T_d$-MoTe$_2$ is determined to have 2-gap $s$-wave symmetry. We also exclude time-reversal symmetry breaking in the superconducting state with zero-field $\mu$SR experiments. Considering the strong suppression of $T_c$ in MoTe$_2$ by disorder, we suggest that topologically non-trivial $s^{+-}$ state is more likely to be realized in MoTe$_2$ than the topologically trivial $s^{++}$ state.

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An interesting physical property of two-dimensional materials such as transition metal dichalcogenides (TMDs) with a common formula, MX2 (M is a transition metal, X is a chalcogen atom), are useful for many emerging technological applications.

The title compound MoTe$_2$ undergoes a structural phase transition from monoclinic 1T’ to orthorhombic $T_d$ at $T_d \approx 250$ K. The 1T’ structure possesses the inversion symmetric space group $P2_1/m$, whereas the $T_d$ phase belongs to the non-centrosymmetric space group $Pmn2_1$. Weyl fermions occur in the $T_d$ phase where the inversion symmetry is broken and $T_d$-MoTe$_2$ is considered to be type-II Weyl semimetal. The evidence for the low temperature $T_d$ structure in our MoTe$_2$ sample is provided by X-ray pair distribution function (PDF) measurements (Supplementary Note 1; Supplementary Figs. 3 and 4).

The Fermi surfaces in a type-II Weyl semimetal consist of a pair of electron pockets and hole pockets touching at the Weyl node, rather than at the point-like Fermi surface in traditional type-I WSM systems. Weyl fermions can arise by breaking either the space-inversion (SIS) or time-reversal symmetry (TRS). The different symmetry classifications of the Weyl semimetals are expected to exhibit distinct topological properties. Recent angle-resolved photoemission (ARPES) measurements and a high-field quantum oscillation study of the magnetoresistance (MR) in $T_d$-MoTe$_2$ revealed a distinctive features of surface states. In addition, Mo$_x$W$_{1-x}$Te$_2$, experimental signatures of the predicted topological connection between the Weyl bulk states and Fermi arc surface states were also reported, constituting another unique property of Weyl semimetals.

$T_d$-MoTe$_2$ represents a rare example of a material with both superconductivity and a topologically non-trivial band structure. At ambient pressure, $T_d$-MoTe$_2$ is superconducting with $T_c \approx 0.1$ K, but the application of a small pressure can markedly enhance $T_c$. $T_d$-MoTe$_2$ is believed to be a promising candidate for topological superconductivity (TSC) in a bulk material. TSCs are materials with unique electronic states consisting of a full pairing gap in the bulk and gapless surface states composed of Majorana fermions (MFs).

In general, topological superfluidity and superconductivity are well-established phenomena in condensed matter systems. The A-phase of superfluid helium-3 constitutes an example of a charge neutral topological superfluid, whereas Sr$_2$RuO$_4$ is generally believed to be topological TRS-breaking superconductor. However, an example of a TRS invariant topological superconductor is thus far unprecedented, and $T_d$-MoTe$_2$ may be a candidate material for this category. Until now, the only known properties of the superconducting state in $T_d$-MoTe$_2$ are the pressure-dependent critical temperatures and fields. Thus, a thorough exploration of superconductivity in $T_d$-MoTe$_2$ from both experimental and theoretical perspectives is required.

To further explore superconductivity and its possible topological nature in $T_d$-MoTe$_2$, it is critical to measure the superconducting order parameter in $T_d$-MoTe$_2$ on the microscopic level through measurements of the bulk properties. Thus, we concentrate on high pressure muon-spin relaxation/rotation (μSR) measurements of the magnetic penetration depth $\lambda$ in $T_d$-MoTe$_2$. This quantity is one of the fundamental parameters of a superconductor, as it is related to the superfluid density $n_s$ via $\lambda^2 = \mu_0 n_s m^*$. Remarkably, the temperature dependence of $\lambda$ is particularly sensitive to the topology of the SC gap: whereas in a nodeless superconductor, $\Delta(T) \equiv \lambda^2(T)/\lambda^2(0)$ vanishes exponentially at low $T$, in a nodal SC it vanishes as a power of $T$. The μSR technique provides a powerful tool to measure $\lambda$ in the vortex state of type-II superconductors in the bulk of the sample, in contrast to many techniques that probe $\lambda$ only near the surface. Details are provided in the "Methods" section. In addition, zero-field μSR has the ability to detect internal magnetic fields as small as 0.1 G without applying external magnetic fields, making it a highly valuable tool for probing spontaneous magnetic fields due to TRS breaking in exotic superconductors.

By combining high-pressure μSR and AC-susceptibility experiments, we observed a substantial increase of the superfluid density $n_s m^*$ and a linear scaling with $T_c$ under pressure. Moreover, the superconducting order parameter in $T_d$-MoTe$_2$ is determined to have 2-gap $s$-wave symmetry. We also excluded time-reversal symmetry breaking in the high-pressure SC state, classifying MoTe$_2$ as time-reversal-invariant superconductor with broken inversion symmetry. Taking into account the previous report on the strong suppression of $T_c$ in MoTe$_2$ by disorder, we suggest that topologically non-trivial $s^\pm$ state is more likely to be realized in MoTe$_2$ than the topologically trivial $s^\mp$ state. Should $s^\pm$ indeed be the SC gap symmetry, the $T_d$-MoTe$_2$ is, to our knowledge, the first known example of a time-reversal-invariant topological (Weyl) superconductor.

### Results

**Probing the vortex state as a function of pressure.** Figure 1a shows the temperature dependence of the AC-susceptibility $\chi_{AC}$ of $T_d$-MoTe$_2$ in the temperature range between 1.4 and 4.2 K for different pressures.

**Fig. 1** AC-susceptibility as a function of temperature and pressure in MoTe$_2$. a Temperature dependence of the AC-susceptibility $\chi_{AC}$ for the polycrystalline sample of MoTe$_2$, measured at ambient and various applied hydrostatic pressures up to $p \approx 1$ GPa. The arrow denotes the superconducting transition temperature $T_c$. b Pressure dependence of $T_c$ (this work) and the structural phase transition temperature $T_d$ of MoTe$_2$. Arrows mark the pressures at which the $T$-dependence of the penetration depth was measured.
the pressure range investigated in this work, MoTe2 is a Weyl semi-metal in which the band structure near the Fermi level is highly sensitive to changes in the lattice constants15. The arrows mark the \( T_c \) values. Inset illustrates how muons, as local probes, sense the inhomogeneous field distribution in the vortex state of type-II superconductor. The error bars represent the s.d. of the fit parameters.

selected hydrostatic pressures up to \( p = 1.9 \) GPa. A strong diamagnetic response and sharp SC transition are observed under pressure (Fig. 1), pointing to the high quality of the sample and providing evidence for bulk superconductivity in MoTe215. The pressure dependence of \( T_c \) is shown in Fig. 1b. \( T_c \) increases with increasing pressure and reaches a critical temperature \( T_c \approx 4 \) K at \( p = 1.9 \) GPa, the maximum applied pressure in the susceptibility experiments. The substantial increase of \( T_c \) from \( T_c \approx 0.1 \) K at ambient pressure to \( T_c \approx 4 \) K at moderate pressures in MoTe2 was considered as a manifestation of its topologically non-trivial electronic structure. Note that a strong pressure-induced enhancement of \( T_c \) has also been observed in topological superconductors such as Bi2Te337 and Bi2Se338. The temperature of the structural phase transition from monoclinic 1T to orthorhombic 3T15 as a function of pressure is also shown in Fig. 1b. In the temperature and pressure range \( (p = 0–1.9 \) GPa) investigated here, MoTe2 is in the orthorhombic 3T structure. Moreover, density functional theory (DFT) calculations confirmed that in the pressure range investigated in this work, MoTe2 is a Weyl semimetal in which the band structure near the Fermi level is highly sensitive to changes in the lattice constants15.

Figure 2a and b displays the transverse-field (TF) \( \mu \)SR-time spectra for MoTe2 measured at \( p = 0.45 \) GPa and the maximum applied pressure \( p = 1.3 \) GPa, respectively, in an applied magnetic field of \( \mu_0H = 20 \) mT. Spectra collected above the SC transition temperature (2 K, 3.5 K) and below it (0.25 K) are shown. The presence of the randomly oriented nuclear moments causes a weak relaxation of the \( \mu \)SR signal above \( T_c \). The relaxation rate is strongly enhanced below \( T_c \), which is caused by the formation of a flux-line lattice (PLL) in the SC state, giving rise to an inhomogeneous magnetic field distribution. Another reason for an enhancement of the relaxation rate could be magnetism, if present in the samples. However, precise zero-field (ZF)-\( \mu \)SR experiments does not show any indication of magnetism in \( T_d \)- MoTe2 down to 0.25 K. This can be seen in ZF time spectra, shown in Fig. 2c, which can be well described only by considering the field distribution created by the nuclear moments39. Moreover, no change in ZF-\( \mu \)SR relaxation rate (see the inset of Fig. 2c) across \( T_c \) was observed, pointing to the absence of any spontaneous magnetic fields associated with a TRS31,40,41 breaking pairing state in MoTe2.

Figure 3 displays the temperature dependence of the muon-spin depolarization rate \( \sigma_{sc} \) (measured in an applied magnetic field of \( \mu_0H = 20 \) mT) in the SC state of MoTe2 at selected pressures. This relaxation rate is proportional to the width of the non-uniform field distribution (see Methods section). The formation of the vortex lattice below \( T_c \) causes an increase of the relaxation rate \( \sigma_{sc} \). As the pressure is increased, both the low-temperature value of \( \sigma_{sc}(0.25 \) K) and the transition temperature \( T_c \) show a substantial increase (Fig. 3). \( \sigma_{sc}(0.25 \) K) increases by a factor of ~2 from \( p = 0 \) GPa to \( p = 1.3 \) GPa. In the following, we show that the observed temperature dependence of \( \sigma_{sc} \), which reflects the topology of the SC gap, is consistent with the presence of the two isotropic s-wave gaps on the Fermi surface of MoTe2.

Pressure-dependent magnetic penetration depth. To explore the symmetry of the SC gap, it is important to note that \( \lambda(T) \) is related to \( \sigma_{sc}(T) \) as follows42:

\[
\frac{\sigma_{sc}(T)}{\sigma_{sc}(T_\mu)} = \frac{\Phi_0}{\lambda_{eff}(T)}.
\]

where \( \Phi_0 \) is the magnetic-flux quantum and \( \gamma_\mu \) denotes the gyromagnetic ratio of the muon. Thus, the flat \( T \)-dependence of \( \sigma_{sc} \) at low temperature observed at various pressures (Fig. 3) implies an isotropic superconducting gap. In this case, \( \lambda_{eff}(T) \) exponentially approaches its zero-temperature value. We note that it is the effective penetration depth \( \lambda_{eff} \) (powder average), which we extract from the \( \mu \)SR depolarization rate (Eq. (1)), and
this is the one shown in the figures. In polycrystalline samples of highly anisotropic systems $\lambda_{\text{eff}}$ is dominated by the shorter penetration depth $\lambda_{\text{ab}}$ and $\lambda_{\text{eff}} = 1.3\lambda_{\text{ab}}$ as previously shown \cite{43, 44}.

The temperature dependence of the penetration depth is quantitatively described within the London approximation ($\lambda \gg \xi$, where $\xi$ is the coherence length) and by using the empirical $\alpha$-model. This model \cite{45-49} assumes, besides common $T_c$, that the gaps in different bands are independent of each other. The superfluid densities, calculated for each component independently \cite{49}, (see details in the "Methods" section) are added together with a weighting factor:

$$\frac{\lambda^{-2}(T)}{\lambda^{-2}(0)} = \alpha \frac{\lambda_{\text{eff}}^{-2}(T, \Delta_{0,1})}{\lambda_{\text{eff}}^{-2}(0, \Delta_{0,1})} + (1-\alpha) \frac{\lambda_{\text{eff}}^{-2}(T, \Delta_{0,2})}{\lambda_{\text{eff}}^{-2}(0, \Delta_{0,2})},$$

where $\lambda_{\text{eff}}(0)$ is the effective penetration depth at zero temperature, $\Delta_{0,i}$ is the value of the $i$-th SC gap ($i = 1,2$) at $T = 0$ K, $\alpha$ and $(1-\alpha)$ are the weighting factors, which measure their relative contributions to $\lambda^{-2}$.

The results of this analysis are presented in Fig. 4a–f, where the temperature dependence of $\lambda_{\text{eff}}^{-2}$ for MoTe$_2$ is plotted at various pressures. We consider two different possibilities for the gap function: either a constant gap, $\Delta_{0,i} = \Delta_i$, or an angle-dependent gap of the form $\Delta_{0,i} = \Delta_i \cos2\varphi$, where $\varphi$ is the polar angle around the Fermi surface. The dashed and the solid lines represent fits to the data using a 1-gap $s$-wave and a 2-gap $s$-wave model, respectively. The analysis supports the simple 1-gap $s$-wave scenario as a description of $\lambda_{\text{eff}}^{-2}(T)$ for MoTe$_2$. The 2-gap $s$-wave model for $p = 0.45$ GPa with $\alpha = 0.12(2)$ meV and a large gap $\Delta_2$ (with the pressure-dependent weighting factor of $1-\alpha = 0.87$), describes the experimental data remarkably well. The possibility of a nodal gap was also tested, shown with a black dotted line in Fig. 4a, but was found to be inconsistent with the data. This conclusion is supported by a $\chi^2$ test, revealing a value of $\chi^2$ for the nodal gap model that is ~30% higher than the one for 2-gap $s$-wave model for $p = 0.45$ GPa. The ratio for the higher gap is consistent with the strong coupling limit BCS expectation \cite{50}. However, a similar ratio can also be expected for Bose Einstein condensation (BEC)-like picture as pointed out in ref. \cite{51}. It is important to note that the ratio $2\Delta/\kappa_i T_c$ does not effectively distinguish between BCS or BEC. This is particularly true in two band systems, where the ratio is not universal even in the BCS limit, as it depends also on the density of states of the two bands. The pressure dependence of various physical parameters are plotted in Fig. 5a and b. From Fig. 5a, a substantial decrease of $\lambda_{\text{eff}}(0)$ (increase of $\sigma_c$) with pressure is evident. At the highest applied pressure of $p = 1.3$ GPa, the reduction of $\lambda_{\text{eff}}(0)$ is ~25% compared with the value at $p = 0.45$ GPa. The small gap $\Delta_1 \approx 0.12(3)$ meV stays nearly unchanged by pressure, whereas the large gap $\Delta_2$ increases from $\Delta_2 \approx 0.29(1)$ meV at $p = 0.45$ GPa to $\Delta_2 \approx 0.49(1)$ meV at $p = 1.3$ GPa, i.e., by ~70%.

In general, the penetration depth $\lambda$ is given as a function of $n_s$, $m^*$, $\xi$, and the mean free path $l$ as

$$\frac{1}{\lambda^2} = \frac{4m^*\xi^2}{\pi\hbar^2} \times \frac{1}{1 + l/\xi^2}.$$ 

For systems close to the clean limit, $\xi/l \rightarrow 0$, the second term essentially becomes unity, and the simple relation $1/\lambda \propto n_i/m^*$ holds. Considering the $H_{cu}$ values of MoTe$_2$ reported in ref. \cite{13}, we estimated $\xi \approx 26$ and 14 nm for $p = 0.45$ and 1 GPa, respectively. At ambient pressure, the in-plane mean free path $l$ was estimated to be $l \approx 100$–200 nm \cite{28}. No estimates are currently available for $l$ under pressure. However, in-plane $l$ is most probably independent of pressure, considering the fact that the effect of compression is mostly between layers rather than within layers, thanks to the unique anisotropy of the van der Waals structure. In particular, the intralayer Mo–Te bond length is almost unchanged.
Fig. 5 Pressure evolution of various quantities. The SC muon depolarization rate $\sigma_{SC}$, magnetic penetration depth $\lambda_{eff}$ and the superfluid density $n_s/m^*_s$ (a) as well as the zero-temperature gap values $\Delta_{SC}(0)$ (b) are shown as a function of hydrostatic pressure. Dashed lines are guides to the eye and solid lines represent linear fits to the data. The error bars represent the s.d. of the fit parameters. c A plot of $T_c$ vs. $\lambda_{eff}(0)$ obtained from our $\mu$SR experiments in MoTe$_2$. The dashed red line represents the linear fit to the MoTe$_2$ data. The Uemura plot for various cuprate and Fe-based HTSs is also shown$^{49,66-70}$. The relation observed for underdoped cuprates is also shown (solid line for hole doping$^{52-55}$ and dashed black line for electron doping$^{50-51}$). The points for various conventional BCS superconductors and for NbSe$_2$ are also shown.

Discussions

One of the essential findings of this paper is the observation of two-gap superconductivity in $T_c$-MoTe$_2$. Recent ARPES$^{27}$ experiments on MoTe$_2$ revealed the presence of three bulk hole pockets (a circular hole pocket around the Brillouin zone center and two butterfly-like hole pockets) and two bulk electron pockets, which are symmetrically distributed along the $\Gamma$-$X$ direction with respect to the Brillouin zone center $\Gamma$. As several bands cross the Fermi surface in MoTe$_2$, two-gap superconductivity can be understood by assuming that the SC gaps open at two distinct types of bands. Now the interesting question arises: How consistent is the observed two-gap superconductivity with the possible topological nature of superconductivity in $T_c$-MoTe$_2$? Note that the superconductor $T_c$-MoTe$_2$ represents a time-reversal-invariant Weyl semimetal, which has broken inversion symmetry. Recently, the detailed studies of microscopic interactions and the SC gap symmetry for time-reversal-invariant TSC in Weyl semimetals have been performed$^{24}$. Namely, it was shown that for TSC the gaps can be momentum independent on each FS but must change the sign between different FSs. $\mu$SR experiments alone cannot distinguish between sing-changing $s^+$ (topological) and $s^+$ (trivial) pairing states. However, considering the recent experimental observations of the strong suppression of $T_c$ in MoTe$_2$ by disorder$^{11,53}$ and the theoretical proposal that TSC is more sensitive to disorder than the ordinary s-wave superconductivity$^{24,34}$, we suggest that $s^+$ state is more likely to be realized than the trivial $s^+$ state. Further phase sensitive experiments are desirable to distinguish between $s^+$ states of $s^+$ and $s^+$ states in MoTe$_2$.

Besides the two-gap superconductivity, another interesting observation is the strong enhancement of the superfluid density $\lambda_{eff}(0) \propto n_s/(m^*_s)$ and its linear scaling with $T_c$ (Fig. 5c). Between $p = 0.45$ and 1.3 GPa, $n_s/(m^*_s)$ increases by factor of ~1.8. We also compared the band structures for ambient as well as for the hydrostatic pressure of 1.3 GPa by means of DFT calculations. The results are shown in Fig. 6. When the pressure is applied, there are appreciable differences of the bands near the Fermi level, especially near $Y-Z$, $T-Z$, and $\Gamma-X$. Near $\Gamma$, the hole band is shifted by +0.8–0.9 eV, whereas the electron band at $Y$ and $T$ are lowered by 20–40 meV.

The nearly linear relationship between $T_c$ and the superfluid density was first noticed in hole-doped cuprates in 1988–1989$^{35,36}$, and its possible relevance to the crossover from BEC to BCS condensation has been discussed in several subsequent papers$^{37-39}$. The linear relationship was noticed mainly in systems lying along the line for which the ratio of $T_c$ to the effective Fermi temperature $T_F$ is about $T_c/T_F \sim 0.05$, implying a reduction of $T_c$ by a factor of 4–5 from the ideal Bose condensation temperature for a non-interacting Bose gas composed of the same number of Fermions pairing without changing their effective masses. The present results on MoTe$_2$ and NbSe$_2$ in Fig. 5c demonstrate that a linear relation holds for these systems, but with the ratio $T_c/T_F$ being reduced by a factor of 16–20. It was also noticed$^{51}$ that electron-doped cuprates follow another line with their $T_c/T_F$ reduced by a factor of ~4 from the line of hole-doped cuprates. As the present system MoTe$_2$ and NbSe$_2$ fall into the clean limit, the linear relation is unrelated to pair breaking, and can be expected to hold between $T_c$ and $n_s/m^*_s$. 

Fig. 6 DFT results. Calculated band structure of $T_c$-MoTe$_2$ at ambient $p$ (solid black curves) and for $p = 1.3$ GPa (dashed red curves)
In a naive picture of BEC to BCS crossover, systems with small $T_c/T_F$ (large $T_F$) are considered to be on the "BCS" side, whereas the linear relationship between $T_c$ and $T_F$ is expected only on the BEC side. Figure 5c indicates that the BEC-like linear relationship may exist in systems with $T_c/T_F$ reduced by a factor 4 to 20 from the ratio in hole-doped cuprates, presenting a new challenge for theoretical explanations.

In conclusion, we provide the first microscopic investigation of the superconductivity in $T_d$-MoTe$_2$. Specifically, the zero-temperature magnetic penetration depth $\lambda_{\text{eff}}(0)$ and the temperature dependence of $\lambda_{\text{eff}}^2(T)$ were studied in the type-II Weyl semimetal $T_d$-MoTe$_2$ by means of $\mu$SR experiments as a function of pressure up to $P \approx 1.3$ GPa. Remarkably, the temperature dependence of $\lambda_{\text{eff}}^2(T)$ is inconsistent with a simple isotropic s-wave pairing symmetry and with presence of nodes in the gap, however, it is well described by a 2-gap s-wave symmetry and with presence of nodes in the gap.

$\lambda_{\text{eff}}^2(T)$ may exist in systems with a magnetic field $H$ parallel to the $c$-axis. We used the following function to describe the $\lambda_{\text{eff}}^2(T)$ dependence of $\mu$SR form factors for the s-wave pairing symmetry and with presence of nodes in the gap.

$$\frac{\lambda_{\text{eff}}^2(T, \Delta_0)}{\lambda_{\text{eff}}^2(0, \Delta_0)} = 1 + \frac{1}{2} \sum_{i=1}^{\infty} \frac{\gamma_i}{E_{\text{ff}} - \Delta_i(T, \phi)^2}$$

where $f = [1 + \exp(E/|k_B|T)]^{-1}$ represents the Fermi function, $\phi$ is the angle along the Fermi surface, and $\Delta_i(T, \phi) = \Delta_0 \sqrt{1/2 + \sqrt{1/4 + (|\phi|/\Delta_0)^2}}$ is the maximum gap value at $T = 0$. The temperature evolution of the gap is given by the expression $T/T_c^0 = 1 - (1.82 + 0.81 T/T_c^0)^{-1}$. We use $\gamma_i = 0.5$ and $\Delta_0 = 0.25 \mu_0$ as the temperature-independent Gaussian relaxation rate, $\mu_i H_{\text{sc}}$ and $\mu_i H_{\text{sc}}$ are the internal magnetic fields measured in the normal and in the SC state, respectively.

$\Delta_i(T)$ were studied in the type-II Weyl semimetal $T_d$-MoTe$_2$ using the details: GPD, Year: 2016, Run Title: MoTe2.

$\lambda_{\text{eff}}$ was employed to classify MoTe$_2$ as a topologically non-trivial electronic structure of $T_d$-MoTe$_2$. We hope the present results will stimulate theoretical investigations to obtain a microscopic understanding of the relation between superconductivity and the topologically non-trivial electronic structure of $T_d$-MoTe$_2$.

Methods

Sample preparation: High quality single crystals and polycrystalline samples were obtained by mixing of molybdenum foil (99.95%) and tellurium lumps (99.999+% in a ratio of 1:20 in a quartz tube and sealed under vacuum. The reagents were heated to 1000 °C within 10 h. They dwelled at this temperature for 24 h, before they were cooled to 900 °C within 30 h (polycrystalline sample) or 100 h (single crystals). At 900 °C the tellurium flux was spun-off and the samples were quenched in air. The obtained MoTe$_2$ samples were annealed at 400 °C for 12 h to rid them of any residual tellurium.

Pressure cell: Single walled CuBe piston-cylinder type of pressure cell is used together with Daphne oil to generate hydrostatic pressures for $\mu$SR experiments. Pressure dependence of the SC critical temperature of tiny indium piece is used to measure the pressure. The fraction of the muons stopping in the sample was estimated to be ~40%.

$\mu$SR experiment: Nearly perfectly spin-polarized, positively charged muons $\mu^+$ are implanted into the specimen, where they behave as very sensitive microscopic magnetic probes. Muon-spin experiences the Larmor precession either in the local field or in an applied magnetic field. Fundamental parameters such as the magnetic penetration depth $\lambda$ and the coherence length $\xi$ can be measured in the bulk of a superconductor by means of transverse-field $\mu$SR technique, in which the magnetic field is applied perpendicular to the initial muon-spin polarization. If a type-II superconductor is cooled below $T_c$ in an applied magnetic field ranging between the lower ($H_L$) and the upper ($H_U$) critical fields, a flux-line lattice is formed and muons will randomly probe the non-uniform field distribution of the vortex lattice. Combination of high-pressure $\mu$SR instrument GPD ($\mu$E1 beamline), the low-background instrument GPD ($\mu$E3 beamline) and the low-temperature instrument LT1 ($\mu$E3.3) of the Paul Scherrer Institute (Villigen, Switzerland) is used to study the single crystal as well as the polycrystalline samples of MoTe$_2$.

Analysis of TF-$\mu$SR data: The following function is used to analyze the TF $\mu$SR data$^{[55]}$.

$$P(t) = A_0 e^{-t/\tau_{\text{app}}} + A_1 e^{-t/\tau_{\text{app}}},$$

where $A_0$ and $A_1$ denote the initial asymmetries of the sample and the pressure cell, respectively. $\gamma/(2\pi) \approx 135$ MHz/T is the gyromagnetic ratio of muon and $\phi$ denotes the initial phase of the muon-spin ensemble. $B_0$ represents the internal magnetic field, sensed by the muons. $\tau_{\text{app}}$ is the relaxation time, caused by the nuclear magnetic moments. The value of $\tau_{\text{app}}$ was obtained above $T_c$ and was kept constant over the entire temperature range. The relaxation rate $\tau_{\text{app}}$ describes the damping of the $\mu$SR signal due to the formation of the vortex lattice in the SC state. $\tau_{\text{app}}$ describes the depolarization due to the nuclear moments of the pressure cell. $\tau_{\text{app}}$ exhibits the temperature dependence below $T_c$ due to the influence of the diamagnetic moment of the SC sample on the pressure cell. $\tau_{\text{app}}$ is the ratio of the field shift of the internal magnetic field in the SC state was assumed to consider the temperature-dependent $\tau_{\text{app}}$ below $T_c$:

$$\tau_{\text{app}}(T) = \tau_{\text{app}}(T > T_c) + C(T)(\mu_i H_{\text{sc}} - \mu_i H_{\text{sc}}).$$

In conclusion, we provide the first microscopic investigation of the superconductivity in $T_d$-MoTe$_2$. Specifically, the zero-temperature magnetic penetration depth $\lambda_{\text{eff}}(0)$ and the temperature dependence of $\lambda_{\text{eff}}^2(T)$ were studied in the type-II Weyl semimetal $T_d$-MoTe$_2$ by means of $\mu$SR experiments as a function of pressure up to $P \approx 1.3$ GPa. Remarkably, the temperature dependence of $\lambda_{\text{eff}}^2(T)$ is inconsistent with a simple isotropic s-wave pairing symmetry and with presence of nodes in the gap, however, it is well described by a 2-gap s-wave symmetry and with presence of nodes in the gap.

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where $f = [1 + \exp(E/|k_B|T)]^{-1}$ represents the Fermi function, $\phi$ is the angle along the Fermi surface, and $\Delta_i(T, \phi) = \Delta_0 \sqrt{1/2 + \sqrt{1/4 + (|\phi|/\Delta_0)^2}}$ is the maximum gap value at $T = 0$. The temperature evolution of the gap is given by the expression $T/T_c^0 = 1 - (1.82 + 0.81 T/T_c^0)^{-1}$. We use $\gamma_i = 0.5$ and $\Delta_0 = 0.25 \mu_0$ as the temperature-independent Gaussian relaxation rate, $\mu_i H_{\text{sc}}$ and $\mu_i H_{\text{sc}}$ are the internal magnetic fields measured in the normal and in the SC state, respectively.

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Data availability. All relevant data are available from the authors. The data can also be found at the following link: http://msruser.psc.uch/cgb-bin/SearchDB/cgi using the details: GPD, Year: 2016, Run Title: MoTe2.
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