Mass of Abrikosov vortex in high-temperature superconductor YBa$_2$Cu$_3$O$_7$–$\delta$

Roman Tesař$^{1,2}$, Michal Šindler$^3$, Christelle Kadlec$^1$, Pavel Lipavský$^2$, Ladislav Skrbek$^2$ & Jan Koláček$^4$

For more than four decades, mass of Abrikosov vortices defied experimental observations. We demonstrate a method of its detection in high-temperature superconductors. Similarly to electrons, fluxons circulate in the direction given by the magnetic field, causing circular dichroism. We report the magneto-transmittance of a nearly optimally doped thin YBa$_2$Cu$_3$O$_{7-\delta}$ film, measured using circularly polarized submillimeter waves. The circular dichroism emerges in the superconducting state and increases with dropping temperature. Our results confirm the dominant role of quasiparticle states in the vortex core and yield the diagonal fluxon mass of $2.2 \times 10^8$ electron masses per centimeter at 45 K and zero-frequency limit, and even larger off-diagonal mass of $4.9 \times 10^8 m_e$ cm$^{-1}$.

The limitations of today’s digital technology will likely be overcome by ultra-fast superconductive electronics, quantum circuits, and quantum information processing. Such advanced electronic devices can operate within the framework of fluxonics taking advantage of intrinsic properties of superconducting vortices. Abrikosov vortices, or fluxons, are ideal information carriers: they are topologically stable and keep a uniform nano-scale size given by quantum conditions.

Nevertheless, the fluxon mass is a particularly controversial issue. Its theoretical estimates are scattered over more than eight orders of magnitude. Vortex mass in superconductors has been debated for over 50 years since its theoretical prediction by Suhl$^5$, 4000 $m_e$/cm for Nb, where $m_e$ is the electron mass. Multiple theories emerged in 1991, stimulated by the discovery of high-$T_c$ superconductors; for instance, the vortex mass in YBaCuO was predicted$^6$ to reach $10^9 m_e$/cm. Rather different trends follow from the theory of Han et al.$^7$, which gives $10^{13} m_e$/cm in Nb at 5 K, while for YBaCuO at the same temperature, it yields $3 \times 10^9 m_e$/cm. Additionally, the vortex mass can be increased by backflow effects$^8$ or by the strain field$^9,10$ with estimates for YBaCuO from dominant $10^{10}$ to negligible $10^4 m_e$/cm. We also note that theories for the mass of quantized vortices in closely related superfluids offer similarly conflicting results$^{11,12}$ that span the full range from the infinite mass$^{13-15}$ to the negligible one$^{16}$.

In contrast to the plethora of theoretical predictions of the effective vortex mass in type-II superconductors, we are aware of only two relevant experiments, both supporting rather large values. Fil et al.$^7$ measured the acousto-electric effect in YBa$_2$Cu$_3$O$_6$ and deduced a vortex mass of $10^{10} m_e$/cm. Golubchik et al.$^{18}$ observed the movement of individual vortices in a superconducting Nb film near its critical temperature by combining high-resolution magneto-optical imaging with ultrafast heating and cooling. A nonzero mass is indispensable to explain their experimental data; they estimated the fluxon mass to be in the interval $(0.3 - 6) \times 10^8 m_e$/cm.

The extremely large spread in theoretically predicted values and scarce experimental data available motivated us to independently determine the mass of a fluxon. Here, we present relevant experiments leading to the evaluation of the vortex mass in a nearly optimally doped YBa$_2$Cu$_3$O$_{7-\delta}$. Our approach is inspired by the cyclotron resonance measurement, a method commonly employed to obtain the effective mass of charge carriers in semiconductors. Exposed to an external magnetic field, charged particles move in circular orbits and, under certain conditions, resonantly absorb monochromatic radiation. In the case of fluxons, however, the cyclotron motion is induced by interaction with circularly polarized far-infrared laser light. This interaction depends on the sense of circular polarization and manifests itself as a differential transmittance for clockwise and anti-clockwise polarized waves, known as magnetic circular dichroism. We show that the theory of Kopnin and coworkers reproduces our experimental data without any fitting parameter. Thus, our results support the theory of the fluxon mass developed by Kopnin and Vinokur$^{19}$ and that of the Magnus force reduction by the factor of Kopnin and Kravtsov$^{20,21}$.

1Institute of Physics, Czech Academy of Sciences, Na Slovance 2, 182 21 Prague 8, Czech Republic. 2Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, 121 16 Prague 2, Czech Republic. 3email: tesar@fzu.cz
Far-infrared measurements of the fluxon mass Magneto-transmittance of circularly polarized light. We designed and developed a unique far-infrared (FIR) transmission experiment capable of probing the circular dichroism (see Fig. 1). The breakthrough that has eventually allowed us to conduct this research is a custom-made retarder inserted in the optical path near the FIR-laser output aperture; it delays the horizontal polarization relative to the vertical one by an adjustable phase difference. A mutual phase shift of \( \pm \frac{\pi}{2} \) converts the THz beam of equal vertical and horizontal polarization components into the circularly polarized state. Since the phase delay introduced by the retarder is inversely proportional to the wavelength of the incoming light, each laser line requires a separate adjustment.

We measured the transmittance of the sample for several laser lines at wavelengths 119, 163, 312, 419, and 433 \( \mu m \), corresponding to the terahertz circular frequencies \( \omega \) of 15.9, 11.6, 6.05, 4.50, and 4.35 \( \times 10^{12} \) rad/s, respectively. Our setup shown in Fig. 1a enables fast flips between clockwise (+) and anti-clockwise (−) circular polarizations; consequently, we probed the transmittance \( T_+ \) and \( T_- \) of both polarizations under identical conditions. The transmittance, i.e., the fraction of laser energy transmitted through the sample, is evaluated as the bolometer-to-pyrodetector signal ratio, effectively eliminating any possible time instability in the laser power. Identical profiles of both signals confirm that the transmittance is measured in the linear regime.

Our experimental protocol is as follows: In experimental runs, we apply a magnetic field at a temperature well above \( T_c \). As the temperature drops, vortices freeze into a regular Abrikosov lattice. The applied magnetic field \( B \) is kept constant since any change in \( B \) would result in inhomogeneous patterns of the vortex density. The temperature \( T \) is swept down and up at a steady sweep rate of 2.5 K/min, the instantaneous temperature of the sample being recorded together with the transmittance. Care is taken to avoid hysteresis of the down and up sweeps.
Figure 2. Sample specification. Panels (a–d) refer to the zero magnetic field. (a) The dc resistivity as a function of temperature provides the critical temperature $T_c = 87.6$ K. Extrapolation of the normal-state resistivity below $T_c$ gives negligible residual resistivity. (b) The imaginary part of conductivity as a function of frequency for several temperatures. The two-fluid model (lines) reproduces the data (symbols) for the superconducting fraction $f_s = 1 - T^2 / T_c^2$ (line), which is compared in (c) with the fitted values. (d) The real (circles) and imaginary (squares) components of the complex conductivity at 100 K provide the relaxation time $\tau_{\text{NL}} = 47$ fs. (e) The measured real part of conductivity for linearly polarized light at magnetic field $7$ T (circles) compared with fits based on the vortex dynamics, $\sigma = \frac{1}{2}(\sigma_+ + \sigma_-)$, supports small pinning with $\kappa = 2 \times 10^5$ N/m².

Figure 1c displays a typical temperature behavior of the transmittance observed in the external magnetic field of 10 T using a 312 µm laser line. The results obtained with different laser lines are similar. As expected, the transmittance measured in zero field does not show any dichroism, in absence of Abrikosov vortices to induce an asymmetry. In nonzero fields, however, the low-temperature circular dichroism is clearly observed and can be attributed to the formation of vortices threading the sample. The effect is enhanced in higher applied magnetic fields, thanks to the growing areal density of Abrikosov vortices (see Fig. 1d). We focus on the low-temperature transmittance measured in zero field does not show any dichroism, in absence of Abrikosov vortices to induce a dichroism. In nonzero fields, however, the low-temperature circular dichroism is clearly observed and can be attributed to the formation of vortices threading the sample. The effect is enhanced in higher applied magnetic fields.

**Sample specification by time-domain terahertz spectroscopy.** We chose the most common high-$T_c$ material $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ in the form of a thin film with a thickness of $L = 107$ nm, and with CuO$_2$ planes parallel to the surface. The sample was prepared at National Chiao Tung University (Taiwan) using a pulsed laser deposition method from a stoichiometric target on a lanthanum aluminate substrate oriented in the (100) plane. The substrate dimensions are $10 \times 10 \times 0.5$ mm$^3$. Several measurements were performed to establish sample properties. Figure 2 summarizes some relevant results.

The critical temperature of the film, $T_c = 87.6$ K, was determined from a dedicated measurement of dc resistivity $\rho$ (Fig. 2a). For our slightly underdoped sample, this $T_c$ corresponds to the hole density $n_h \approx 1.68 \times 10^{27}$ /m$^3$. The linear slope of $\rho$ extrapolated to zero temperature shows negligible residual resistivity, so the relaxation time is inversely proportional to temperature.

Additional film properties were established in a separate experiment using standard time-domain THz spectroscopy. Broadband linearly polarized THz pulses (0.3–2.5 THz) were generated by exciting an interdigitated LT-GaAs emitter with a Ti:sapphire femtosecond laser beam at 800 nm. We measured the complex conductivity $\sigma = \sigma' + i\sigma''$ for frequencies $\omega/2\pi$ in the range 0.5–2 THz at temperatures from 4 to 100 K (Fig. 2b,d,e). At the zero magnetic field and below $T_c$, the two-fluid model fit confirms the dominant London contribution, $\sigma_0 \approx \frac{\kappa}{\omega m_0}$, with a temperature-dependent condensate density $n = n_0 (1 - T^2 / T_c^4)$, the hole mass $m = 3.3 m_e$, and the elementary charge $e$. Comparing the conductivities at temperatures of 4 K and $T_{NL} = 100$ K in Fig. 2d, we found the relaxation time $\tau_{\text{NL}} = 5 \times 10^{-14}$ s. Conductivities at all temperatures from 4 to 100 K are consistent with $\tau = \tau_{\text{NL}} T / T_N$.

Our sample is moderately clean. Its purity is given by the lifetime measured on the energy scale$^{35}$ as $k_B^2 T_c^2 \tau / h E_F$, where $k_B$ is the Boltzmann constant and $h$ is the reduced Planck constant. The Fermi energy $E_F = \hbar^2 k_F^2 / 2m$ depends on the hole doping. For the hole density of our sample, the Fermi surface is cylindrical rather than spherical, and the Fermi momentum follows from the 2D density of holes in the CuO$_2$ plane $n_{2D} = n_{2D} / 2 = k_F^2 / (2\pi)$, where $c = 11.68$ Å is the YBa$_2$CuO$_4$ lattice parameter in the $c$-direction. The resulting Fermi energy $E_F = 71$ meV yields the value of $k_B T_c^2 / h E_F \approx 0.1$, corresponding to the moderately clean sample.

According to Kopnin and Vinokur$^{36}$, the moderately clean d-wave superconductor behaves as the $s$-wave one. In the absence of reliable formulas for angular frequency $\omega_0$ of quasiparticles bounded in the vortex core in the d-wave superconductors, we used $\omega_0 = (\Delta_0 / k_F^2)(1 - T^2 / T_c^2)$ for the conventional
superconductors. We deduced the coherence length $\xi_0$ from the upper critical field in the zero-temperature limit, $B_c \approx 122 \ T = \Phi_0 / 2\pi \xi_0^2$, where $\Phi_0$ is the magnetic flux quantum. From the energy gap $2\Delta_0 = 4.3k_B T_c$, we obtained $\omega_0 = 4.4 \times 10^{12} \text{rad/s}$, a value close to $4.5 \times 10^{12} \text{rad/s}$ of our 419 $\mu$m laser line.

To complete the sample characteristics, we assume the pinning of vortices by layer imperfections, for example, the surface roughness. Figure 2e shows the conductivity in the magnetic field of 7 T applied perpendicularly to the film. It was interpreted either with the theory specified below or with the model used by Parks, both indicating that the vortex pinning is rather weak with the Labusch coefficient $\kappa \approx 2 \times 10^5 \text{N/m}^2$.

**Theoretical prediction.** Our aim is to compare experimental values of $T_+/T_-$ with a theoretical model. Using the above sample parameters, we can evaluate the film conductivity $\sigma_\perp$ from which the transmittance $T_\perp$ results. The theoretical prediction shown in Fig. 3 is based on the Yeh formalism and covers interferences in the film/substrate structure. Its amplitude is smaller than the experimental error. The values observed under identical conditions but in different runs hang on the same vertical line attached to the surface. Despite the experimental uncertainty, the overall magnitude and dependence on magnetic field and wavelength are consistent with the Kopnin–Vinokur theory.

**Figure 3.** Transmittance ratio $T_+/T_-$ for the laser lines 119, 163, 312, 419, and 433 $\mu$m as a function of magnetic field. The theoretical prediction (colored surface) with no free fitting parameter is compared with experimental values (spheres) observed at a temperature of 45 K. The corrugation of the theoretical surface results from interference in the film/substrate structure. Its amplitude is smaller than the experimental error. The values observed under identical conditions but in different runs hang on the same vertical line attached to the surface. These repeated measurements demonstrate a spread of the experimental data. Despite the experimental uncertainty, the overall magnitude and dependence on magnetic field and wavelength are consistent with the Kopnin–Vinokur theory.
The diagonal mass $\mu_{\parallel}$ is complex at finite frequencies, which reflects a delay between a change of the vortex velocity and a change of the total momentum of quasiparticles in its core. The off-diagonal mass $\mu_{\perp}$ describes a property common in anisotropic systems that the velocity of an excitation is not parallel with its momentum. Quasiparticles disturbed by the vortex motion and the action of FIR light eventually lose their momentum in collisions with impurities and phonons. Via these collisions, the crystal lattice acts on the fluxon by force $F$. With the collision integral approximated by a single relaxation time $\tau$, the force and the momentum are simply related by $F = -p/\tau$. The longitudinal force $-(\mu_{\parallel}/\tau)v$ is a vortex friction. The transversal force $(\mu_{\perp}/\tau)[v \times z]$ reduces the Magnus force giving the Kopnin–Kravtsov force$^{20,21}$ in the dc limit.

The electric field in the film$^{32-35}$

$$E = \frac{1}{\sigma_0} J - [v \times B] \tag{3}$$

has a skin component $J/\sigma_0$ from the penetrating incident light and an electric field $-[v \times B]$ generated by the vortex motion. At low frequencies, the London conductivity $\sigma_0$ diverges, and the electric field achieves the dc form of the Josephson relation. In the absence of the magnetic field, Eq. (3) reduces to the London formula. Alternatively, one can employ the Coffey-Clem model used by Parks et al.$^{30}$, which is equivalent to Eq. (3).

Conductivities $\sigma_\pm$ are diagonal elements of the conductivity tensor $\sigma$ in the helical basis. Eigen-vectors of circularly polarized light are constructed from basis vectors in the film plane, e.g., the electric field $E = E_{\pm} e^{-iωt} e_{\pm}$, where $e_{\pm} = (x \pm iy)/\sqrt{2}$ are vectors of the helical basis and $s = \text{sign}(B \cdot k)$ reflects the parallel or the anti-parallel orientation of the applied magnetic field $B$ with respect to the wavevector $k$ of incoming light. The eigen-vectors satisfy $[e_{\pm} \times z] = \pm i e_{\pm}$; therefore, each of the vector equations (1) and (3) splits into two independent scalar equations for $(\pm)$ and $(\mp)$ polarizations. One can easily eliminate the velocity $v$ and write the conductivities

$$\frac{1}{\sigma_{\pm}} = \frac{E_{\pm}}{J_{\pm}} = \frac{1}{\sigma_0} + \frac{B}{en} \left( \frac{ω_0 τ}{1 - iωτ + iω_0 τ} + i\frac{κ}{π\hbar Ω} \right)^{-1} \tag{4}$$

needed for the theoretical prediction of the transmittance.

Discussion

Experiment versus theoretical prediction. With the full set of sample parameters established from the time-domain spectroscopy, the simplified Kopnin–Vinokur conductivity (4) furnishes us with the theoretical prediction of the circular dichroism. Figure 3 compares this prediction and the experimentally observed dichroism. Figure 3 compares this prediction and the experimentally observed dichroism. The observed trends can be understood in terms of Eq. (3). The field dependence arises from the dominant London contribution $1/\sigma_0$ complemented by the Josephson-type resistivity, which is linear in $B$. The variation with wavelength has a similar cause: for lower frequencies, the London resistivity $1/\sigma_0 \approx -iωm/(ne^2)$ is smaller so the Josephson part becomes dominant.

Vortex mass from experiment. Figure 3 documents that the theory of Kopnin and Vinokur is relevant for the THz dynamics of vortices. Since the observed frequency dependence of magneto-transmission agrees with the theoretical one, even with no adjustable parameters, the extrapolation of our results to low frequencies is justified. Based on this, we used their theory to find the vortex mass from our data.

While the sample parameters $n$, $\sigma_0$, and $\tau$ are sound, $κ$ and $ω_0$ are less clear. The Labusch parameter $κ$ has a minor effect on the dichroism; therefore, we kept the value $κ = 2 \times 10^6 \text{N/m}^2$. The angular frequency $ω_0$ was established by the least-square fit of $T_\omega/T_\sigma$ data. The best-fit value $ω_0 = 4.3 \times 10^{14} \text{rad/s}$ was very close to $4.4 \times 10^{15} \text{rad/s}$ estimated above. We believe that such close agreement of observed and estimated frequency is fortuitous.

At THz frequencies, where the circular dichroism was found, both diagonal and off-diagonal masses are complex. They become real in the low-frequency limit, as apparent from Eq. (2). Using the experimentally established values of $ω_0 = 4.3 \times 10^{14} \text{rad/s}$ and other sample parameters, we evaluated the zero-frequency components of the fluxon mass. In YBa$_2$Cu$_3$O$_7-δ$ at 45 K, the diagonal mass $\mu_{\parallel}$ amounts to $2.2 \times 10^8 m_e$/cm, while the off-diagonal mass $\mu_{\perp}$ is more than twice larger, $4.9 \times 10^8 m_e$/cm.

In summary, we have developed a reliable experimental method to measure the circular dichroism of superconducting films threaded by Abrikosov vortices. To interpret our data in terms of vortex dynamics, we have established all the essential material parameters from independent time-domain THz spectroscopy and dc-resistivity measurements. The observed dichroism is in good agreement with the theory of Kopnin and Vinokur based on the circular motion of quasiparticles in the vortex core. Their angular frequency was experimentally determined and used to extrapolate the vortex mass from THz frequencies to low-frequency motion.

Received: 14 June 2021; Accepted: 19 October 2021
Published online: 05 November 2021

References

1. Anders, S. et al. European roadmap on superconductive electronics—Status and perspectives. Physica C 470, 2079 (2010).
2. King, A. D. et al. Observation of topological phenomena in a programmable lattice of 1800 qubits. Nature 560, 456 (2018).
3. Golod, T., Iovan, A. & Krasnov, Y. Single Abrikosov vortices as quantized information bits. Nat. Commun. 6, 8628. https://doi.org/10.1038/ncomms9628 (2015).
4. Vlasko-Vlasov, V. K., Colauto, F., Benseman, T., Rosenmann, D. & Kwock, W.-K. Triode for magnetic flux quanta. Sci. Rep. 6, 36847. https://doi.org/10.1038/srep36847 (2016).
5. Suhl, H. Inertial mass of a moving fluid. Phys. Rev. Lett. 14, 226 (1965).
6. Coffey, M. W. & Hao, Z. Dipolar electric field induced by a vortex moving in an anisotropic superconductor. Phys. Rev. B 44, 5230 (1991).
7. Han, J. H., Kim, J. S., Kim, M. J. & Ao, P. Effective vortex mass from microscopic theory. Phys. Rev. B 71, 125108 (2005).
8. Sonin, E. B. Transverse force on a vortex and vortex mass: Effects of free bulk and vortex-core bound quasiparticles. Phys. Rev. B 87, 154515 (2013).
9. Simánek, E. Inertial mass of a fluxon in a deformable superconductor. Phys. Lett. A 154, 309 (1991).
10. Coffey, M. W. Deformable superconductor model for the fluxon mass. Phys. Rev. B 49, 9774 (1994).
11. Toikka, L. A. & Brand, J. Asymptotically solvable model for a solitonic vortex in a compressible superfluid. New J. Phys. 19, 023029 (2017).
12. Simula, T. Vortex mass in a superfluid. Phys. Rev. A 97, 023609 (2018).
13. Popov, V. N. Quantum vortexes and phase-transition in Bose systems. Zh. Eksp. Teor. Fiz. 64, 672 (1973).
14. Popov, V. N. Quantum vortexes and phase-transition in Bose systems. Sov. Phys. JETP 37, 341 (1973).
15. Duan, J. M. Mass of a vortex line in superfluid $^4$He: Effects of gauge-symmetry breaking. Phys. Rev. B 49, 12381 (1994).
16. Baym, G. & Chandler, E. The hydrodynamics of rotating superfluids. I. Zero-temperature, nondissipative theory. J. Low Temp. Phys. 50, 57 (1983).
17. Fil, V. D. et al. Mass of an Abrikosov vortex. Low Temp. Phys. 33, 1019 (2007).
18. Golubchik, D., Polturak, E. & Koren, G. Mass of a vortex in a superconducting film measured via magneto-optical imaging plus ultrafast heating and cooling. Phys. Rev. B 85, 060504 (2012).
19. Kopnin, N. B. & Vinokur, V. M. Dynamic vortex mass in clean Fermi superfluids and superconductors. Phys. Rev. Lett. 81, 3952 (1998).
20. Kopnin, N. B. & Kravtsov, V. E. Conductivity and Hall effect of pure type-II superconductors at low temperatures. Pis'ma Zh. Eksp. Teor. Fiz. 33, 631 (1981).
21. Kopnin, N. B. & Kravtsov, V. E. Conductivity and Hall effect of pure type-II superconductors at low temperatures. JETP Lett. 23, 578 (1976).
22. Tesář, R., Sindler, M., Koláček, J. & Skrbek, L. Terahertz wire-grid circular polarizer tuned by lock-in detection method. Rev. Sci. Instrum. 89, 083114 (2018).
23. Tesář, R. et al. Terahertz transmission of NbN superconductor thin film. Physica C 470, 932 (2010).
24. Liang, R., Bonn, D. A. & Hardy, W. N. Evaluation of CuO$_2$plane hole plane hole doping in YBa$_2$Cu$_{4-x}$O$_8$, single crystals. Phys. Rev. B 73, 180505(R) (2006).
25. Blumenschein, N. et al. Dielectric and conducting properties of unintentionally and Sn-doped $\beta$-Ga$_2$O$_3$ studied by terahertz spectroscopy. J. Appl. Phys. 127, 165702 (2020).
26. Sonin, E. B. Dynamics of Quantised Vortices in Superfluids (Cambridge University Press, 2016).
27. Welp, U., Kwock, W. K., Crabtree, G. W., Vandervoort, K. G. & Liu, J. Z. Magnetic measurements of the upper critical field of YBa$_2$Cu$_{3-y}$O$_{y-3}$ single crystals. Phys. Rev. Lett. 62, 1908 (1989).
28. Sindler, M. et al. Far-infrared electrodynamic of thin superconducting NbN film in magnetic field. Supercond. Sci. Technol. 27, 055009 (2014).
29. Kadlec, E. et al. Electromagnon in the Z-type hexaferrite (Ba$_3$Sr$_{1-x}$)$_{2}$Co$_{4}$Fe$_{24}$O$_{41}$. Phys. Rev. B 94, 024419 (2016).
30. Parks, B. et al. Phase-sensitive measurements of vortex dynamics in the terahertz domain. Phys. Rev. Lett. 74, 3265 (1995).
31. Višňovský, Š. Optics in Magnetic Multilayers and Nanostructures (CRC Press, 2006).
32. Supplementary Information. https://doi.org/10.1038/s41598-021-00846-x
33. Kopnin, N. B. & Vinokur, V. M. Superconducting vortices in ac fields: Does the Kohn theorem work? Phys. Rev. Lett. 87, 017003 (2001).
34. Sonin, E. B. Interaction of ultrasound with vortices in type-II superconductors. Phys. Rev. Lett. 76, 2794 (1996).
35. Lin, P.-J., Lipavský, P. & Matlock, P. Inertial Josephson relation for FIR frequencies. Phys. Lett. A 376, 883 (2012).

Acknowledgements
We thank Chih-Wei Luo for preparing the YBaCuO sample and for providing the temperature dependence of dc resistivity. The authors are grateful to E. B. Sonin for his kind help with the finite-frequency modification of the equation of vortex motion and to T. Simula and G. E. Volovik for valuable comments. We acknowledge the support of the Czech Science Foundation (project No. 21-11089S), P. L. that of INTER-EXCELLENCE (COST) ICT 18024, C. K. SOLID21-CZ.02.1.01/0.0/0.0/16 019/0000760 and L. S. thanks the Czech Science Foundation (project No. 20-00918S).

Author contributions
J.K. designed the experiment; R.T. developed the circular polarizer and built the experimental setup; R.T. and M.S. performed the measurement of dichroism; C.K. performed the time-domain THz measurements; P.L., M.S., L.S., and J.K analyzed the results. All authors contributed to the discussions and production of the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-021-00846-x.
Correspondence and requests for materials should be addressed to R.T.
Reprints and permissions information is available at www.nature.com/reprints.
Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
