Ultralow-temperature thermal conductivity of the Kitaev honeycomb magnet $\alpha$-RuCl$_3$ across the field-induced phase transition

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Recently, there have been increasingly hot debates on whether there exists a quantum spin liquid in the Kitaev honeycomb magnet $\alpha$-RuCl$_3$ in high magnetic field. To investigate this issue, we perform the ultralow-temperature thermal conductivity measurements on the single crystals of $\alpha$-RuCl$_3$ down to 80 mK and up to 9 T. Our experiments clearly show a field-induced phase transition occurring at $H_c \approx 7.5$ T, above which the zigzag magnetic order is completely suppressed. The minimum of thermal conductivity at 7.5 T is attributed to the strong scattering of phonons by the magnetic fluctuations. Most importantly, above 7.5 T, we do not observe any significant contribution of thermal conductivity from gapless magnetic excitations, which puts a strong constraint on the nature of the high-field phase of $\alpha$-RuCl$_3$.

In transition-metal compounds with partially filled 4$d$ or 5$d$ shells, various novel quantum phases of matter can be brought onto stage, depending on the delicate balance (or the disruption of it) among crystal-field effects, spin-orbit coupling (SOC), and electronic correlation [1]. An incarnation of this competition is the spin-orbit assisted Mott gap opening and the formation of Mott insulator, in which with the help of an enhanced incarnation of this competition is the spin-orbit assisted orbit coupling (SOC), and electronic correlation [1]. An (or the disruption of it) among crystal-field effects, spin-be brought onto stage, depending on the delicate balance or 5$d$ electronic correlation of the 4$d$ electrons identified in both Raman scattering [17, 18] and $\alpha$-perturbations occurring at $H_c \approx 7.5$ T, above which the zigzag magnetic order is completely suppressed. The minimum of thermal conductivity at 7.5 T is attributed to the strong scattering of phonons by the magnetic fluctuations. Most importantly, above 7.5 T, we do not observe any significant contribution of thermal conductivity from gapless magnetic excitations, which puts a strong constraint on the nature of the high-field phase of $\alpha$-RuCl$_3$.

To access the potential QSL state in $\alpha$-RuCl$_3$, a reasonable practice would be to suppress the magnetic order by external tuning parameters, such as the magnetic field or pressure. When applying a magnetic field in the honeycomb plane, the zigzag magnetic order is fully suppressed by $H_c \approx 8$ T, the value varies slightly in different studies), and the high-field phase after the destruction of the zigzag magnetic order has become the research hotspot recently [14, 15, 22, 29]. As for the magnetic excitations in the high-field phase, some studies indicate a gapped scenario [26, 27], while others suggest a gapless one [28, 29].

Thermal conductivity measurements have proven to be a powerful technique in probing the elementary excitations in QSL candidates [31–33]. There have already been three works on the thermal conductivity $\kappa$ of $\alpha$-RuCl$_3$ [25, 28, 30]. The high-temperature thermal conductivity exhibits a broad peak around 110 K, which was attributed to itinerant spin excitations due to Kitaev couplings [30]. Leahy et al. reported that the $\kappa$ shows a striking enhancement with linear growth above the critical field $H_c \sim 7$ T, which was explained as the behavior of proximate Kitaev excitations (PKE) [28]. More recently, the in-plane and c-axis thermal conductivity are found to show similar behavior in magnetic field, which suggests that the unusual magnetic field dependence is the result of severe scattering of phonons off putative Kitaev-Heisenberg excitations, i.e., of phononic origin [25]. The measurements in all three works are conducted at a relatively high temperature range, so that information about the asymptotic behaviors of $\kappa/T$ at $T \rightarrow 0$, which is crucial for the understanding of the ground state, cannot be obtained.

In this Letter, we report the ultralow-temperature thermal conductivity measurements on a high-quality $\alpha$-RuCl$_3$ single crystal down to 80 mK. A field-induced phase transition is clearly resolved at $H_c \sim 7.5$ T. More-
over, in the high-field phase of $\alpha$-RuCl$_3$, no significant contribution to $\kappa$ from magnetic excitations is detected. Instead, we find that magnetic excitations only affect the phonon thermal conductivity by scattering. We will discuss the implications of our findings on the high-field phase of $\alpha$-RuCl$_3$.

Single crystals of $\alpha$-RuCl$_3$ were grown by the chemical vapor transport method [20]. The single crystal exhibits a plate-like shape, as shown in the inset of Fig. 1(c). Its large natural surface was determined to be the (001) plane by using an x-ray diffractometer (D8 Advance, Bruker), as illustrated in Fig. 1(c). Magnetization measurements were performed in commercial SQUID and physical property measurement system (PPMS) (Quantum Design). The specific heat was measured in the PPMS by the relaxation method. The $\alpha$-RuCl$_3$ single crystal for the thermal conductivity measurements was cut into a rectangular shape of dimensions $2.01 \times 1.08$ mm$^2$ in the $ab$ plane, with a thickness of 0.09 mm along the $c$ axis. Four silver wires were directly attached to the sample with silver paint. The thermal conductivity was measured in a dilution refrigerator, using a standard four-wire steady-state method with two RuO$_2$ chip thermometers, calibrated in situ against a reference RuO$_2$ thermometer. Magnetic fields were applied within the large natural surface (the $ab$ plane) and perpendicular to the heat current.

Figure 1(a) shows the illustration of edge-sharing RuCl$_6$ octahedra in $\alpha$-RuCl$_3$. There exist two Ru-Cl-Ru exchange paths (dashed lines), which exhibit a nearly 90° bonding geometry. Such a superexchange process has proven to be crucial for inducing anisotropic Kitaev interactions in strongly spin-orbit coupled compounds [34]. The in-plane honeycomb structure of $\alpha$-RuCl$_3$, where edge-sharing RuCl$_6$ octahedra form a honeycomb network, is shown in Fig. 1(b). Temperature dependence of the magnetic susceptibility at $H = 0.1$ T $\parallel ab$ and the specific heat in zero field for the $\alpha$-RuCl$_3$ single crystal is plotted in Fig. 1(d). It can be clearly seen that there is only one magnetic phase transition at 8 K from $\chi$ and $C_p$. In earlier studies, the single crystals exhibit two magnetic phase transitions at $T_{N1} \approx 8$ K and $T_{N2} \approx 14$ K [12, 14, 15]. The lower (higher) temperature transition is due to the ABC(AB)-type stacking of the honeycomb layers [11]. The single crystals with a single transition at $T_{N1} \approx 8$ K are ideal for the study of the physics in $\alpha$-RuCl$_3$ [19, 20, 24, 29, 30].

FIG. 1. (a) Illustration of edge-sharing RuCl$_6$ octahedra that give rise to a dominant Kitaev exchange interactions in $\alpha$-RuCl$_3$. Dashed lines are two Ru-Cl-Ru exchange paths exhibiting a nearly 90° bonding geometry. Ru and Cl atoms are displayed by pink and yellow balls, respectively. (b) The $ab$-plane structure of $\alpha$-RuCl$_3$, where edge-sharing RuCl$_6$ octahedra form a honeycomb network. (c) Room-temperature x-ray diffraction pattern from the large natural surface of the $\alpha$-RuCl$_3$ single crystal. Only (00l) Bragg peaks show up, indicating that the large natural surface is $ab$ plane. Inset: the optical image of a typical $\alpha$-RuCl$_3$ single crystal. (d) Temperature dependence of the magnetic susceptibility at $H = 0.1$ T $\parallel ab$ and the specific heat in zero field for the $\alpha$-RuCl$_3$ single crystal.

obtained Curie-Weiss temperatures $\Theta_c \approx -132$ K and $\Theta_{ab} \approx 45$ K indicate the effective antiferromagnetic and ferromagnetic exchange interactions, respectively. The effective moments obtained from $\chi_c$ and $\chi_{ab}$ are 2.47 $\mu_B$ and 2.15 $\mu_B$, both larger than the spin-only value of 1.73 $\mu_B$ for the low-spin state of Ru$^{3+}$, suggesting a possibly significant contribution from the orbital moment $\{22\}$. The magnetic susceptibility of the $\alpha$-RuCl$_3$ single crystal in various magnetic fields up to 9 T ($H \parallel ab$) are plotted in Fig. 2(b). With increasing fields, the phase transition
FIG. 2. (a) Temperature dependence of inverse magnetic susceptibility for the α-RuCl₃ single crystal in a magnetic field $H = 0.1$ T applied both parallel and perpendicular to the $ab$ plane. The black lines are fits to the Curie-Weiss law. (b) The magnetic susceptibility of the α-RuCl₃ single crystal in various magnetic fields up to 9 T ($H \parallel ab$). (c) A schematic $T$-$H$ phase diagram for α-RuCl₃, where $T_N$ is obtained from the kink in the $\chi(T)$ curve. The zigzag magnetic order disappears at a critical field $H_c \sim 7.5$ T.

gradually shifts towards lower temperatures and eventually disappears above $\sim 7.5$ T. These results are summarized in the $T$-$H$ phase diagram, as shown in Fig. 2(c), where the transition temperature $T_N$ is determined by the kink in the $\chi(T)$ curve. The heat transport behavior across the field-induced phase transition is the focus of current study.

Figure 3(a) and 3(b) show the in-plane thermal conductivity of the α-RuCl₃ single crystal in zero and finite magnetic fields. As the magnetic field is increased, the $\kappa/T$ first increases slightly for $H < 4$ T, then drops rapidly until 7.5 T, followed by a sharp increase. The minimum $\kappa/T$ at $\sim 7.5$ T corresponds to $H_c$, where the zigzag magnetic order disappears. Such a minimum of $\kappa/T$ was also observed in previous thermal conductivity experiments [25,28], which likely results from the strong scattering of phonons by magnetic fluctuations at the critical point. The sharp

FIG. 3. (a) and (b) The in-plane thermal conductivity of the α-RuCl₃ single crystal in zero and finite magnetic fields. (c) Field dependence of the $\kappa/T$ at $T = 0.2, 0.3, 0.4$, and 0.6 K, respectively. For all curves, the $\kappa/T$ first increases slightly for $H < 4$ T, then drops rapidly until 7.5 T, followed by a sharp increase. The minimum $\kappa/T$ at $\sim 7.5$ T corresponds to $H_c$, where the zigzag magnetic order disappears.
increase of $\kappa(H)$ above $H_c$ was explained in terms of two different scenarios [25–28]. In Ref. [28], the linear rise of the $\kappa$ is interpreted as the contribution from the gapless PKE. However, based on the similar behavior of $\kappa_{ab}(H)$ and $\kappa_c(H)$, Hentrich et al. argued that the $\kappa$ of $\alpha$-RuCl$_3$ is purely contributed by phonons, and the magnetic excitations do not contribute to $\kappa$ but can scatter phonons strongly [25]. With increasing fields above $H_c$, the magnetic excitations are increasingly gapped out, thus reducing the scattering, leading to the enhancement of phonon thermal conductivity $\kappa$ [25]. To clearly examine whether there is contribution to $\kappa$ from the gapless magnetic excitations, it is essential to know the asymptotic behaviors of $\kappa/T$ at $T \to 0$, reflecting the nature of the ground state.

In Fig. 4(a), we first fit the zero-field data below 0.4 K to $\kappa/T = a + bT^{\alpha - 1}$, in which the two terms $aT$ and $bT^{\alpha}$ represent contributions from itinerant fermionic excitations (if they exist) and phonons, respectively [35–36]. Because of the specular reflections of phonons at the sample surfaces, the power $\alpha$ in the second term is typically between 2 and 3 [35–36]. The fitting gives $\kappa_0/T \equiv a = 0.007 \pm 0.011$ mW K$^{-2}$ cm$^{-1}$ and $\alpha = 2.52 \pm 0.09$. Considering our experimental error bar $\pm 0.005$ mW K$^{-2}$ cm$^{-1}$, the $\kappa_0/T$ at zero field is virtually zero. Such a pure phonon thermal conductivity at zero field is reasonable, since $\alpha$-RuCl$_3$ is an insulator with a magnon gap in the zigzag magnetic state [11–20]. Recently, a theoretical calculation relevant to $\alpha$-RuCl$_3$ based on the quantum Monte Carlo simulation found that itinerant Majorana fermions from the fractionalization of quantum spins can carry heat and contribute a finite residual linear term $\kappa_0/T$ [37]. Therefore, if the magnetic excitations are gapless in the high-field phase of $\alpha$-RuCl$_3$, e.g., the PKE suggested in Ref. [28], one may expect a finite residual linear term $\kappa_0/T$. However, by fitting the 8.5 T data to $\kappa/T = a + bT^{\alpha - 1}$, we obtain $\kappa_0/T = -0.002 \pm 0.009$ mW K$^{-2}$ cm$^{-1}$ and $\alpha = 2.33 \pm 0.05$, as in Fig. 4(a). Furthermore, we plot the field dependence of $\kappa_0/T$ across the field-induced phase transition in Fig. 4(b). All of these values are found to be negligible in our field range. Therefore, the absence of $\kappa_0/T$ above the critical field $H_c$ demonstrates the lack of gapless magnetic excitations in the high-field phase of $\alpha$-RuCl$_3$, such as massless Majorana fermions [28]. In other words, our ultralow-temperature thermal conductivity measurements do not support the gapless scenarios of the high-field phase in $\alpha$-RuCl$_3$.

Indeed, a field-induced gapped QSL state has been predicted in $\alpha$-RuCl$_3$ in the field range of $8 \sim 15$ T by exact diagonalization and density-matrix renormalization group calculations for extended Kitaev-Heisenberg spin Hamiltonians [38]. Experimentally, a field-induced gap opening has also been reported in several experiments including inelastic neutron scattering [21], nuclear magnetic resonance [24–27], specific heat [23, 26], and thermal conductivity measurements [28]. The enhancement of thermal conductivity in the high-field phase may be explained by the increasing gap scenario [25].

We would like to discuss the gap amplitude near the critical field $H_c$. The results of a previous thermal conductivity study and a specific heat study suggest that the loss of magnetic order at $H_c$ is accompanied by the closing of the magnetic excitation gap [25–26]. In that case, there should be direct contribution to $\kappa_0/T$ from the gapless magnetic excitations at $H_c$, which is not observed in our data. This indicates that either (a) the gap is still finite at $H_c$, as suggested by another specific heat study with the extrapolation of the gap from high fields [23]; or (b) the gap vanishes around $H_c$, i.e., the gapless magnetic excitations do exist, but are localized so that they cannot conduct heat, possibly owing to magnetic defects [24] or crystallographic domains [26].

Note that there is also a more general theoretical scenario, ascribing the continuum observed by inelastic neutron scattering in $\alpha$-RuCl$_3$ to incoherent excitations originating from strong magnetic anharmonicitity [39], instead of the most discussed explanation referring to a...
coherent continuum of fractional excitations analogous to the celebrated Kitaev spin-liquid. We are not clear what the thermal conductivity behavior is if this more general scenario is the case in $\alpha$-RuCl$_3$.

In summary, we have measured the thermal conductivity of a $\alpha$-RuCl$_3$ single crystal down to 80 mK and up to 9 T. The field dependence of the thermal conductivity exhibits a minimum around 7.5 T, where the field-induced phase transition takes place. The extrapolation of the thermal conductivity down to zero temperature reveals no significant contribution from itinerant gapless fermiinic excitations in the high-field phase. These results impose clear constraints on the nature of the high-field phase and are also expected to help distinguish between theoretical scenarios proposed recently.

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[1] W. Witzczak-Krempa, G. Chen, Y. B. Kim, and L. Balents, Correlated quantum phenomena in the strong spin-orbit regime, Annu. Rev. Condens. Matter Phys. 5, 57 (2014).
[2] B. J. Kim, Hosub Jin, S. J. Moon, J.-Y. Kim, B.-G. Park, C. S. Lee, Jaejun Yu, T. W. Noh, C. Kim, S.-J. Oh, J.-H. Park, V. Durairaj, G. Cao, and E. Rotenberg, Novel $J_{\text{eff}} = 1/2$ Mott State Induced by Relativistic Spin-Orbit Coupling in Sr$_2$IrO$_4$, Phys. Rev. Lett. 110, 076402 (2008).
[3] B. J. Kim, H. Ohsumi, T. Komesu, S. Sakai, T. Morita, H. Takagi, and T. Arima. Phase-sensitive observation of a spin-orbital Mott state in Sr$_2$IrO$_4$. Science 323, 1329 (2009).
[4] A. Kitaev, Anyons in an exactly solved model and beyond, Ann. Phys. (Amsterdam) 321, 2 (2006).
[5] J. Chaloupka, G. Jackeli, and G. Khaliullin, Kitaev-Heisenberg Model on a Honeycomb Lattice: Possible Exotic Phases in Iridium Oxides $\text{A}_2\text{IrO}_3$, Phys. Rev. Lett. 105, 027204 (2010).
[6] Y. Singh and P. Gegenwart, Antiferromagnetic Mott insulating state in single crystals of the honeycomb lattice material Na$_2$IrO$_3$, Phys. Rev. B 82, 064412 (2010).
[7] X. Liu, T. Berlijn, W.-G. Yin, W. Ku, A. Tselik, Y.-J. Kim, H. Gretarsson, Y. Singh, P. Gegenwart, and J. P. Hill, Long-range magnetic ordering in Na$_2$IrO$_3$, Phys. Rev. B 83, 220403 (2011).
[8] S. K. Choi, R. Coldea, A. N. Kolmogorov, T. Lancaster, I. I. Mazin, S. J. Blundell, P. G. Radaelli, Y. Singh, P. Gegenwart, K. R. Choi, S.-W. Cheong, P. J. Baker, C. Stock, and J. Taylor, Spin Waves and Revised Crystal Structure of Honeycomb Iridate Na$_2$IrO$_3$, Phys. Rev. Lett. 108, 127204 (2012).
[9] K. W. Plumb, J. P. Clancy, L. J. Sandilands, V. Vijay Shankar, Y. F. Hu, K. S. Burch, Hae-Young Kee, and Young-June Kim, $\alpha$-RuCl$_3$: A spin-orbit assisted Mott insulator on a honeycomb lattice, Phys. Rev. B 90, 041112(R) (2014).
[10] Duke J. Sandilands, Yao Tian, Anjan A. Reijnders, Heung-Sik Kim, K. W. Plumb, Young-June Kim, Hae-Young Kee, and Kenneth S. Burch, Spin-orbit excitations and electronic structure of the putative Kitaev magnet $\alpha$-RuCl$_3$, Phys. Rev. B 93, 075144 (2016).
[11] A. Banerjee, C. A. Bridges, J.-Q. Yan, A. A. Aczel, L. Li, M. B. Stone, G. E. Granroth, M. D. Lumsden, Y. Yu, J. Knolle, S. Bhattacharjee, D. L. Kovrizhin, R. Moessner, D. A. Tennant, D. G. Mandrus, and S. E. Nagler, Proximate Kitaev quantum spin liquid behaviour in a honeycomb magnet, Nat. Mater. 15, 733 (2016).
[12] J. A. Sears, M. Songvilay, K. W. Plumb, J. P. Clancy, Y. Qiu, Y. Zhao, D. Parshall, and Y.-J. Kim, Magnetic order in $\alpha$-RuCl$_3$: A honeycomb-lattice quantum magnet with strong spin-orbit coupling, Phys. Rev. B 91, 144420 (2015).
[13] H. B. Cao, A. Banerjee, J.-Q. Yan, C. A. Bridges, M. D. Lumsden, D. G. Mandrus, D. A. Tennant, B. C. Chakoumakos, and S. E. Nagler, Low-temperature crystal and magnetic structure of $\alpha$-RuCl$_3$, Phys. Rev. B 93, 134423 (2016).
[14] Y. Kubota, H. Tanaka, T. Ono, Y. Narumi, and K. Kindo, Successive magnetic phase transitions in $\alpha$-RuCl$_3$: XY-like frustrated magnet on the honeycomb lattice, Phys. Rev. B 91, 094422 (2015).
[15] M. Majumder, M. Schmidt, H. Rosner, A. A. Tsirlin, H. Yaszouka, and M. Baenitz, Anisotropic Ru$^{3+}$ 4d$^7$ magnetism in the $\alpha$-RuCl$_3$ honeycomb system: Susceptibility, specific heat, and zero-field NMR, Phys. Rev. B 91, 180401(R) (2015).
[16] S.-Y. Park, S.-H. Do, K.-Y. Choi, D. Jang, T.-H. Jang, J. Schefer, C.-M. Wu, J. S. Gardner, J. M. S. Park, J.-H. Park, and S. Ji, Emergence of the isotropic Kitaev honeycomb lattice with two-dimensional Ising universality in $\alpha$-RuCl$_3$, arXiv:1609.05690 (2016).
[17] L. J. Sandilands, Y. Tian, K. W. Plumb, Y.-J. Kim, and K. S. Burch, Scattering Continuum and Possible Fractionalized Excitations in $\alpha$-RuCl$_3$, Phys. Rev. Lett. 114, 147201 (2015).
[18] J. Nasu, J. Knolle, D. L. Kovrizhin, Y. Motome, and R. Moessner, Fermionic response from fractionalization in an insulating two-dimensional magnet, Nat. Phys. 12, 912 (2016).
[19] A. Banerjee, J. Yan, J. Knolle, C. A. Bridges, M. B. Stone, M. D. Lumsden, D. G. Mandrus, D. A. Tennant, R. Moessner, and S. E. Nagler, Neutron scattering in the proximate quantum spin liquid $\alpha$-RuCl$_3$, Science 356, 1055 (2017).
[20] K. Ran, J. Wang, W. Wang, Z.-Y. Dong, X. Ren, S. Bao, S. Li, Z. Ma, Y. Gan, Y. Zhang, J. T. Park, G. Deng, S. Danilkin, S.-L. Yu, J.-X. Li, and J. Wen, Spin-Wave Excitations Evidencing the Kitaev Interaction in Single Crystalline $\alpha$-RuCl$_3$, Phys. Rev. Lett. 118, 107203.
A. Banerjee, P. Lampen-Kelley, J. Knolle, C. Balz, A. A. Aczel, B. Winn, Y. Liu, D. Pajerowski, J.-Q. Yan, C. A. Bridges, A. T. Savici, B. C. Chakoumakos, M. D. Lumsden, D. A. Tennant, R. Moessner, D. G. Mandrus, and S. E. Nagler, Excitations in the field-induced quantum spin liquid state of $\alpha$-RuCl$_3$, arXiv:1706.07003.

R. D. Johnson, S. C. Williams, A. A. Haghighirad, J. Singleton, V. Zapf, P. Manuel, I. I. Mazin, Y. Li, H. O. Jeschke, R. Valentí, and R. Coldea, Monoclinic crystal structure of $\alpha$-RuCl$_3$ and the zigzag antiferromagnetic ground state, Phys. Rev. B 92, 235119 (2015).

J. A. Sears, Y. Zhao, Z. Xu, J. W. Lynn, and Y.-J. Kim, Phase diagram of $\alpha$-RuCl$_3$ in an in-plane magnetic field, Phys. Rev. B 95, 180411(R) (2017).

S.-H. Baek, S.-H. Do, K.-Y. Choi, Y. S. Kwon, A. U. B. Wolter, S. Nishimoto, J. van den Brink, and B. Büchner, Evidence for a Field-Induced Quantum Spin Liquid in $\alpha$-RuCl$_3$, Phys. Rev. Lett. 119, 037201 (2017).

R. Hentrich, A. U. B. Wolter, X. Zotos, W. Brenig, D. Nowak, A. Isaeva, T. Doert, A. Banerjee, P. Lampen-Kelley, D. G. Mandrus, S. E. Nagler, J. Sears, Y.-J. Kim, B. Büchner, and C. Hess, Large field-induced gap of Kitaev-Heisenberg paramagnons in $\alpha$-RuCl$_3$, arXiv:1703.08623.

A. U. B. Wolter, L. T. Corredor, L. Janssen, K. Nenkov, S. Schöneck, S.-H. Do, K.-Y. Choi, R. Albrecht, J. Hunger, T. Doert, M. Vojta, and B. Büchner, Field-induced quantum criticality in the Kitaev system $\alpha$-RuCl$_3$, Phys. Rev. B 96, 041405(R) (2017).

N. Janša, A. Zorko, M. Gomilšek, M. Pregelj, K. W. Krämer, D. Biner, A. Biffin, Ch. Rüegg, and M. Klanjšek, Observation of gapped anyons in the Kitaev honeycomb magnet under a magnetic field, arXiv:1706.08455.

I. A. Leahy, C. A. Pocs, P. E. Siegfried, D. Graf, S.-H. Do, K.-Y. Choi, B. Normand, and M. Lee, Anomalous Thermal Conductivity and Magnetic Torque Response in the Honeycomb Magnet $\alpha$-RuCl$_3$, Phys. Rev. Lett. 118, 187203 (2017).

J. Zheng, K. Ran, T. Li, J. Wang, P. Wang, B. Liu, Z. Liu, B. Normand, J. Wen, and W. Yu, Gapless spin excitations in the field-induced quantum spin liquid phase of $\alpha$-RuCl$_3$, arXiv:1703.08474.

D. Hirobe, M. Sato, Y. Shiomi, H. Tanaka, and E. Saitoh, Magnetic thermal conductivity far above the Néel temperature in the Kitaev-magnet candidate $\alpha$-RuCl$_3$, Phys. Rev. B 95, 241112(R) (2017).

M. Yamashita, N. Nakata, Y. Kasahara, T. Sasaki, N. Yoneyama, N. Kobayashi, S. Fujimoto, T. Shibuchi, and Y. Matsuda, Thermal-transport measurements in a quantum spin-liquid state of the frustrated triangular magnet $\kappa$-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$, Nat. Phys. 5, 44 (2009).

M. Yamashita, N. Nakata, Y. Senshu, M. Nagata, H. M. Yamamoto, R. Kato, T. Shibuchi, and Y. Matsuda, Highly mobile gapless excitations in a two-dimensional candidate quantum spin liquid, Science 328, 1246 (2010).

Y. Xu, J. Zhang, Y. S. Li, Y. J. Yu, X. C. Hong, Q. M. Zhang, and S. Y. Li, Absence of Magnetic Thermal Conductivity in the Quantum Spin-Liquid Candidate YbMgGaO$_4$, Phys. Rev. Lett. 117, 267202 (2016).

G. Jackeli and G. Khaliullin, Mott Insulators in the Strong Spin-Orbit Coupling Limit: From Heisenberg to a Quantum Compass and Kitaev Models, Phys. Rev. Lett. 102, 017205 (2009).

M. Sutherland, D. G. Hawthorn, R. W. Hill, F. Ronning, S. Wakimoto, H. Zhang, C. Proust, E. Boaknin, C. Lupien, L. Taillée, R. X. Liang, D. A. Bonn, W. N. Hardy, R. Gagnon, N. E. Hussey, T. Kimura, M. Nohara, and H. Takagi, Thermal conductivity across the phase diagram of cuprates: Low-energy quasiparticles and doping dependence of the superconducting gap, Phys. Rev. B 67, 174520 (2003).

S. Y. Li, J. B. Bonnemaison, A. Payeur, P. Fournier, C. H. Wang, X. H. Chen, and L. Taillée, Low-temperature phonon thermal conductivity of single-crystalline Nd$_2$CuO$_4$: Effects of sample size and surface roughness, Phys. Rev. B 77, 134501 (2008).

J. Nasu, J. Yoshitake, and Y. Motome, Thermal Transport in the Kitaev Model, arXiv:1703.10395 Phys. Rev. Lett., in press.

R. Yadav, N. A. Bogdanov, V. M. Katukuri, S. Nishimoto, J. van den Brink, and L. Hozoi, Kitaev exchange and field-induced quantum spin-liquid states in honeycomb $\alpha$-RuCl$_3$, Sci. Rep. 6, 37925 (2016).

S. M. Winter, K. Riedel, A. Honecker, and R. Valentí, Breakdown of Magnons in a Strongly Spin-Orbital Coupled Magnet, arXiv:1702.08466.