Rare-Earth Chalcogenides: A Large Family of Triangular Lattice Spin Liquid Candidates

Weilei Liu(刘维维), Zheng Zhang(张政), Jianting Ji(籍建亭), Yixuan Liu(刘以轩), Jianshu Li(李建成), Xiaojun Wang(王孝群), Hechang Lei(雷和畅), Gang Chen(陈钢), Qingming Zhang(张清明)

1 National Laboratory for Condensed Matter Physics and Institute of Physics, Chinese Academy of Sciences, Beijing 100190
2 Department of Physics and Beijing Key Laboratory of Opto-electronic Functional Materials & Micro-nano Devices, Renmin University of China, Beijing 100872
3 Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240
4 State Key Laboratory of Surface Physics and Department of Physics, Fudan University, Shanghai 200433
5 School of Physical Science and Technology, Lanzhou University, Lanzhou 730000

(Received 24 September 2018)

Frustrated quantum magnets are expected to host many exotic quantum spin states like quantum spin liquid (QSL), and have attracted numerous interest in modern condensed matter physics. The discovery of the triangular lattice spin liquid candidate YbMgGaO$_4$ stimulated an increasing attention on the rare-earth-based frustrated magnets with strong spin-orbit coupling. Here we report the synthesis and characterization of a large family of rare-earth chalcogenides AR$e$Ch$_2$ (A = alkali or monovalent ions, Re = rare earth, Ch = O, S, Se). The family compounds share the same structure (R3m) as YbMgGaO$_4$, and antiferromagnetically coupled rare-earth ions form perfect triangular layers that are well separated along the c-axis. Specific heat and magnetic susceptibility measurements on NaYb$_2$O$_4$, NaYb$_2$S$_4$ and NaYb$_2$Se$_4$ single crystals and polycrystals, reveal no structural or magnetic transition down to 50 mK. The family, having the simplest structure and chemical formula among the known QSL candidates, removes the issue on possible exchange disorders in YbMgGaO$_4$. More excitingly, the rich diversity of the family members allows tunable charge gaps, variable exchange coupling, and many other advantages. This makes the family an ideal platform for fundamental research of QSLs and its promising applications.

PACS: 75.10.Kt, 75.30.Et, 75.30.Gw DOI: 10.1088/0256-307X/35/11/117501

The concept of quantum spin liquids (QSLs) was originally proposed by P. W. Anderson theoretically over 40 years ago.[1] It describes a highly entangled quantum state for spin degrees of freedom and was initially constructed with a superposition of spin singlets on the triangular antiferromagnet, so-called resonating-valence-bond state.[1] Later on, the possible connection between QSLs and high-temperature superconductivity was theoretically established through doping a QSL Mott insulator.[2] Although the underlying mechanism for the high-temperature superconductivity has not yet come into a consensus, our understanding of QSLs has greatly improved, both from exactly solvable models[3,4] and several classification schemes.[5,6] On the experimental side, various frustrated magnetic materials, particularly the triangular-lattice-based antiferromagnets, were considered to be the most promising systems to realize QSLs.[6] So far, a number of compounds have been reported to host QSLs. Among them, the well-known ones include herbertsmithite and its derived compounds,[7-14] and triangular organics.[15-19] The magnetic ions in most of these compounds are 3d transition metal ions Cu$^{2+}$ with $S = 1/2$, which may be crucial to enhance quantum fluctuations.

Quite recently, frustrated materials with magnetic rare-earth ions are proposed to be promising QSL candidates.[20] These include the well-known pyrochlore ice materials,[21-30] the kagome magnet,[31,32] and the triangular lattice magnets.[33-47] The local degree of freedom for the rare-earth ions that contain an odd number of 4f electrons (excluding Gd$^{3+}$) is a Kramers doublet and can be mapped to an effective spin $S = 1/2$ degree of freedom. This effective-spin local moment is protected by time reversal symmetry and the point group symmetry. In many cases the non-Kramers rare-earth ions can be taken as effective spin $S = 1/2$ local moments at low temperatures, though lacking the protection from time reversal symmetry.[26,30,47-49] The spin-orbit-entangled nature of the rare-earth local moments often brings highly anisotropic spin models that have never been constructed and studied before.[26,45-49] Thus, the rare-earth-based magnets play an important role in the exploration of novel spin models and the exotic magnetic states on various lattices. Indeed, QSL behaviors and multipolar phases have been proposed for various rare-earth compounds.[21-30,32,46,47]

*Supported by the Ministry of Science and Technology of China under Grant Nos 2016YFA0300504, 2017YFA0302904 and 2016YFA0301001, and the Natural Science Foundation of China under Grant Nos 11774419, 11474357, 11822412, 11774423 and 11574394.

†These authors contributed equally to this work.

**Corresponding authors. Email: hlei@ruc.edu.cn; chggst@gmail.com; qmzhang@iphy.ac.cn

© 2018 Chinese Physical Society and IOP Publishing Ltd
The recent discovery of the triangular lattice magnet YbMgGaO₄ has invoked a further interest in the search of spin liquids with strong spin-orbit coupling. The compound has a space group symmetry of R3m, and the Yb²⁺ ions form a flat and perfect triangular lattice. The availability of high-quality single crystals allows extensive and careful studies of magnetic properties using neutron scattering, electron spin resonance (ESR), etc. These studies point to a possible gapless U(1) QSL ground state. On the other hand, some experiments and theoretical arguments raised the issue on Ga/Mg disorder, which was suggested to be responsible for the disordered spin state and/or QSL stability. The small exchange coupling allows an easy tunability of the spin state with a laboratory magnetic field. Meanwhile, it also requires that most experiments must be carried out at ultralow temperatures. In some cases this could be an obstacle for in-depth studies and possible applications.

As mentioned above, there is a long list of rare-earth magnets. Then the question is if one can find out some interesting compounds or systems with larger exchange couplings and without disorder. This is the purpose of this work. We systematically synthesized the rare-earth chalcogenides AReCh₂ (A = alkali or monovalent ions, Re = rare earth, Ch = O, S, Se) with a delafossite structure. We carried out the structural and thermodynamic characterizations of these compounds. The compounds have a high symmetry of R3m and perfect spin triangular layers. The magnetic measurements indicate that spins are antiferromagnetically coupled in all the compounds with a range of Curie–Weiss temperatures. For the representative NaYbCh₂ (Ch = O, S, Se) samples, no magnetic ordering or transition is observed in the specific heat and susceptibility measurements down to 50 mK. Thus, this is a large family of QSL candidates with the simplest structure and chemical formula so far. Its crystal structure naturally removes the issue on Ga/Mg disorder proposed for YbMgGaO₄. The diversity of the large family makes it an ideal playground for studying the QSL physics and exploring its promising applications.

![Diagram](Image)

**Fig. 1.** The general crystal structure of rare-earth chalcogenides and the powder diffraction patterns and Rietveld refinements for NaYbCh₂ (Ch = O, S, Se).

The polycrystals of NaReO₂ (Re = Yb, Lu) were synthesized by the method of solid-state reaction under high temperatures:

\[
\text{Na}_2\text{CO}_3 + \text{Re}_2\text{O}_3 \rightarrow 2\text{NaReO}_2 + \text{O}_2 \quad (\text{Re} = \text{Yb, Lu}).
\]

(1)

Na₂CO₃ and Re₂O₃ powders were mixed in a dry process (mixing molar ratio: Na₂O:Yb₂O₃ = 2.5:1) and shocked into a pellet by isostatic pressing (50 MPa, 2 min). Shaped samples were heated at 900°C for 9 hours. After the heating, the samples were ground and washed with distilled water and ethanol, lastly dried in air at room temperature for 48 hours. The polycrystals of NaReS₂ (Re = La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) were synthesized by the method of solid-state reaction under high temperature:

\[
\text{Na}_2\text{S} + 2\text{Re} + 3\text{S} \rightarrow 2\text{NaReS}_2,
\]

(2)

where Re = Lu, Se, Tm, Er, Ho, Dy, Tb, Gd, Eu, Sm, Nd, Pr, Ce, La. The Na₂S, Re and S powder was...
mixed in an Ar environment glove box. The mixed powders were placed in a graphite crucible and vacuum packaged with quartz tube. Packaged samples were heated at 850 °C for 48 hours. After the heating, the sample was powder and washed with distilled water and then dried in air at 50 °C for 6 hours. The synthesis of polycrystals of NaReSe₂ (Re = Er, Yb, Lu) were similar with the synthesis of powders of NaReS₂. The temperature was adjusted to 900 °C. We have also successfully grown high quality NaYbSe₂ single crystals. The growth conditions of single crystals are more rigorous than NaYbSe₂ crystals. Na₂Se, Yb and Se powders were mixed in Ar environment glove box (mixing molar ratio: Na₂Se:Yb:Se = 1:2:12). The mixed powder was placed in special quartz tube that can withstand higher pressure. Packaged samples were headed at 1000 °C for 48 hours. After the heating, we can observe 2-3 mm size single crystals. We made a simple resistance check for the crystals and the resistance is overranged and thus NaYbSe₂ is confirmed to be a good insulator.

Powder XRD profiles were measured with Bruker D8 by step scanning. The TOPAS program was used for Rietveld crystal structure refinements. The temperature dependence of magnetic susceptibility from 1.8 K to 300 K was measured with a SQUID magnetometer (Quantum Design Magnetic Property Measurement System, MPMS) under both ZFC and FC for all the samples with the brass sample holder. The AC susceptibility measurements from 50 mK to 4 K were performed using a dilution refrigeration system (DR). The polycrystalline sample was pressed into a thin plate and fixed on a sample holder with GE varnish. The heat capacity measurements from 2 K to 30 K were performed using PPMS (Quantum Design Physical Property Measurement System) and DR was employed for the measurements from 50 mK to 4 K. The plate sample was mounted on a sample holder with N grease for a better thermal contact.

Table 1. Parameters extracted from Curie–Weiss fitting for NaYbCh₂ (Ch = O, S, Se).

| Ch | Space group | C | θCW (K) | μeff (μB) |
|----|-------------|---|---------|-----------|
| O  | R3m        | 1.9448 | −77.35  | 4.94      |
| S  | R3m        | 2.6166 | −40.98  | 4.57      |
| Se | R3m        | 2.2550 | −59.84  | 4.24      |

In Fig. 1, we depict the crystal structure of the rare-earth chalcogenides and the Rietveld refinements for three representative samples NaYbO₂, NaYbS₂ and NaYbSe₂, where the detailed structural information extracted from the refinements can be found in the Supplementary Materials. The system has an R3m space group symmetry, and the magnetic ions form flat triangular layers that are well separated. The ReCh₄ octahedra are connected in an edge-sharing fashion. The local crystal-field environment around the magnetic ions is exactly analogous to the case of YbMgGaO₄. Therefore, one expects a similar crystal-field splitting scheme of the Yb³⁺ ions as the one in YbMgGaO₄. This means that a spin-orbital-entangled effective spin S = 1/2 local moment should hold for our case. Similar to YbMgGaO₄, the antisymmetric Dzyaloshinskii-Moriya interaction is prohibited by the inversion symmetry of the system.

![Fig. 2](image-url)
The Mg/Ga disorder in the non-magnetic layers of YbMgGaO₄ has been extensively discussed and is still under debate. Whether or how much this non-magnetic disorder impacts on the Yb magnetic properties is unclear in this stage. In some experiments and theoretical calculations, the disorder was considered to play a dominant role in contributing to the low-energy excitations. As a comparison, there is no such disorder in this family of rare-earth chalcogenides, due to the structural simplicity. The issue on disorder is completely removed for this family of materials. We further made the analysis of element ratio (see Supplementary Materials), which is close to the nominal ratio. This rules out the possibility of the disorder caused by element deficiency. If one still concerns about the active monovalent ions like Na⁺ and K⁺, he will have plenty of choices of the heavy monovalent ones such as Rb⁺, Cs⁺, Cu⁺ and Ag⁺.

For the selected sub-family NaYbCH₂ (Ch = O, S, Se), we measured the DC magnetic susceptibility in the range of 2–300 K and the AC susceptibility from 50 mK to 4 K. The results are presented in Fig. 2. The Curie–Weiss fitting was made from 150 K to 300 K according to the crystal-field splitting in YbMgGaO₄ and the fitting results are summarized in Table 1. Considering the small interaction energy scale of rare-earth moments, this fitting range may not be quite sufficient to characterize the low-energy magnetic physics of the system. A lower fitting range may be required in the future. Nevertheless, the negative Curie–Weiss temperatures suggest an antiferromagnetic coupling in all the samples. Excitingly, the Curie–Weiss temperatures are much larger than that of YbMgGaO₄ because of the smaller distances between nearest-neighbor Yb³⁺ in the rare-earth chalcogenides. The AC susceptibility for the three samples shows no sign of long-range magnetic ordering. The measurements under various frequencies further confirms that there is no spin freezing either. Interestingly, the susceptibility saturation in the zero temperature limit is clearly observed for all the three samples. This should be one of the consequences caused by strong spin-orbit coupling rather than a sign of finite density of spin excitations. Under the strong spin-orbit coupling, the total magnetization is not a good quantum number and cannot be used to label the many-body eigenstate. The many-body eigenstate would be a mixture of states with different total magnetizations. The magnetic susceptibility would always be a constant. We also find that the low-temperature susceptibility of NaYbSe₂ is obviously larger than that of the other two compounds. In fact, the distance between nearest neighbor Yb³⁺ ions in NaYbSe₂ is larger, while its Curie–Weiss temperatures and the moment obtained from the Curie–Weiss fitting look comparable to the other two.

![Fig. 3.](image)

**Fig. 3.** Specific heat measurements on NaYbCH₂ (Ch = O, S, Se). Single crystal (SC) NaYbSe₂ and polycrystalline NaYbO₂ and NaYbS₂ were used in the measurements.

Our specific heat results are shown in Fig. 3. There is no obvious transition down to 50 mK in these compounds, and it is consistent with the conclusion from the magnetic susceptibility data. We observed no apparent change or shift with applying a magnetic field up to 3 T (see Fig. 3(c)). On the other hand, an upturn is observed below 100 mK in the C/T–T plot (see Fig. 3(d)). This may arise from the nuclear Schottky
anomaly due to the nuclear spins. The upturn makes it difficult to obtain the intrinsic trend of the specific heat below 100 mK and to conclude whether the system is a gapless or gapped QSL. Thus, more detailed magnetic and thermodynamic experiments are required in the future. The broad peak around 1 K in the $C/T \cdot T$ plot is considered to be a consequence of preserving entropy. Here we point out that there is no obvious disorder in the present case and we still do not observe any long-range magnetic ordering or freezing that points to a possible QSL ground state. This means that the rare-earth triangular system, including rare-earth chalcogenides reported here and YbMgGaO$_4$, intrinsically hosts the QSL state that is not stabilized by or even originated from the Ga/Mg charge disorder.

The Curie–Weiss fitting was performed from 150 K to 300 K, assuming a reasonably high crystal field splitting. The full results are presented in Table 2. We can see that the exchange couplings vary from sample to sample. In the other words, we have the opportunity to select the compounds with various exchange coupling. Beyond this, one can further tune the charge gaps of the family members by element substitution. The absorption spectra (see Supplementary Materials) indicate that the charge gaps are roughly 4.5 eV, 2.7 eV and 1.9 eV for NaYbO$_2$, NaYbS$_2$, and NaYbSe$_2$, respectively. The variable and small charge gaps may allow the system to access a Mott-metal transition by applying doping or pressures. Such a possibility opens up the interesting direction of Mott transitions out of a QSL.[57] This transition was argued to be continuous by noticing that the Landau damping term scales like a mass term for the bosonic charge and then identifying the transition as an usual superfluid-Mott transition.[57] Thus, these exciting advantages stem from the rich diversity of the family. In fact, we have made a careful literature research and found that most of the family members have the high symmetry of $R3m$ and hence are potential QSL materials (see Supplementary Materials). This suggests that the family is an ideal playground, on which we can tune the basic material parameters or exchange coupling to explore the QSL physics and develop its possible applications.

Table 2. Parameters extracted from the Curie–Weiss fitting for NaReS$_2$ (Re = Ce–Yb).

| Re   | Space group | C    | $\theta_{CW}$ (K) | $\mu_{eff}$ (Obs.) | $\mu_{eff}$ (Cal.) |
|------|-------------|------|-------------------|--------------------|--------------------|
| Ce   | Fm$\overline{3}$m | 1.1145 | $-164.42$ | 2.99$\mu_B$ | 2.54$\mu_B$ |
| Pr   | Fm$\overline{3}$m | 1.91757 | $-57.48$ | 3.92$\mu_B$ | 3.58$\mu_B$ |
| Nd   | $R3m$      | 1.78198 | $-25.35$ | 3.71$\mu_B$ | 3.62$\mu_B$ |
| Sm   | $R3m$      | 0.71761 | $-343.05$ | 2.40$\mu_B$ | 0.84$\mu_B$ |
| Eu   | $R3m$      | 3.19082 | $-106.13$ | 5.05$\mu_B$ | 3.6$\mu_B$ |
| Gd   | $R3m$      | 8.5521 | $-1.98$ | 8.27$\mu_B$ | 7.94$\mu_B$ |
| Tb   | $R3m$      | 12.87953 | $-9.49$ | 10.15$\mu_B$ | 9.72$\mu_B$ |
| Dy   | $R3m$      | 14.55906 | $-9.39$ | 10.79$\mu_B$ | 10.63$\mu_B$ |
| Ho   | $R3m$      | 13.8468 | $-5.90$ | 10.52$\mu_B$ | 10.6$\mu_B$ |
| Er   | $R3m$      | 12.13713 | $-4.62$ | 9.85$\mu_B$ | 9.59$\mu_B$ |
| Tm   | $R3m$      | 7.40589 | $-3.83$ | 7.69$\mu_B$ | 7.57$\mu_B$ |
| Yb   | $R3m$      | 2.90963 | $-63.74$ | 4.8$\mu_B$ | 4.54$\mu_B$ |

In summary, we have synthesized rare-earth chalcogenides $\text{AReCh}_2$ that exhibit a delafossite structure, and made structural and thermodynamics characterizations. The family has a lattice symmetry $R3m$, and the magnetic ions are antiferromagnetically coupled and form perfect triangular layers. The magnetic susceptibility and specific heat measurements down to 50 mK indicate no sign of long-range magnetic ordering or transition. The family removes the disorder issue raised in YbMgGaO$_4$ and also suggests the QSL physics is probably not from disorder. The unique advantages, such as various charge gaps and exchange coupling, suggest that the family may be an ideal platform for the further study of QSLs.
We thank Zicheng Wen for assisting the absorption measurements and Feng Jin for organizing the references.

Note added: Upon the completion of this work, we became aware of Ref. [58] that focused on NaYbS2 and proposed it as a spin liquid candidate.

References

[1] Anderson P W 1973 Mater. Res. Bull. 8 153
[2] Lee P A, Nagaosa N and Wen X G 2006 Rev. Mod. Phys. 78 17
[3] Kitaev A 2006 Ann. Phys. 321 2
[4] Wen X G 2007 Quantum Field Theory of Many-Body Systems (Oxford University Press)
[5] Essin A M and Hermele M 2013 Phys. Rev. Lett. 110 087202
[6] Balents L 2010 Nature 464 199
[7] Helton J S, Matan K, Shores M P, Nytko E A, Bartlett B M, Yoshida Y, Takano Y, Suzlov A, Qiu Y, Chung J H., Nocera D G and Lee Y S 2007 Phys. Rev. Lett. 98 170724
[8] Han T H, Helton J S, Chu S Y, Nocera D G, Rodriguez R, Jose A, Broholm C and Lee Y S 2012 Nature 492 406
[9] Olariu A, Mendels P, Bert F, Duc F, Trombe J C, de Vries M A and Harrison A 2008 Phys. Rev. Lett. 100 087202
[10] Yoshikawa Y, Hiroyuki Y and Zenji H 2009 J. Phys. Soc. Jpn. 78 033701
[11] Zenji H, Masafumi H, Naoya K, Minoru N, Hidenori T, Yoshimoto K and Masashi T 2001 J. Phys. Soc. Jpn. 70 3377
[12] Yoshida M, Takigawa M, Yoshida H, Okamoto Y and Hiroi Z 2009 Phys. Rev. Lett. 103 077207
[13] Li Y S Pan B Y, Li S Y, Tong W, Ling L S, Yang Z R, Nocera D G and Lee Y S 2007 Phys. Rev. Lett. 98 107204
[14] Zorko A, Nellutla S, van Tol J, Brunel L C, Bert F, Duc F, Trombe J C, de Vries M A and Harrison A 2008 Phys. Rev. Lett. 101 026405
[15] Itou T, Oyamada A, Maegawa S, Tamura M and Kato R 2007 J. Phys.: Condens. Matter 19 145247
[16] Itou T, Oyamada A, Maegawa S, Tamura M and Kato R 2008 Phys. Rev. B 77 104413
[17] Shimizu Y, Miyagawa K, Kanoda K, Maesato M and Saito G 2003 Phys. Rev. Lett. 91 107001
[18] Satooshi Y, Yasuhiro N, Masaharu O, Yugo O, Hirohuki N, Yasuhiro S, Kazuya M and Kazushii K 2008 Nat. Phys. 4 459
[19] Kurusaki Y, Shimizu Y, Miyagawa K, Kanoda K and Saito G 2005 Phys. Rev. Lett. 95 177001
[20] Gardner J S, Gingras M J P and Greedan J E 2010 Rev. Mod. Phys. 82 53
[21] Gardner J S, Dunsiger S R, Gaulin B D, Gingras M J P, Greedan J E, Kiedl R F, Lumond M D, MacFarlane W A, Raja N P, Sonier J E, Swainson I and Tun Z 1999 Phys. Rev. Lett. 82 1012
[22] Ross K A, Ruff J P C, Adams C P, Gardner J S, Dachsowska H A, Qiu Y, Copley J R D and Gaulin B D 2009 Phys. Rev. Lett. 103 227202
[23] Prinece A J, Prabhakaran D, Boothroyd A T and Adroja D T 2013 Phys. Rev. B 88 104421
[24] Ross K A, Savary L, Gaulin B D and Balents L 2011 Phys. Rev. X 1 021002
[25] Molavina H R, Ginsaras M J P and Canals B 2007 Phys. Rev. Lett. 98 157204
[26] Onoda S and Tanaka Y 2010 Phys. Rev. Lett. 105 047201
[27] Applegate R, Hayre N R, Singh R R P, Lin T, Day A G R, Gingras and M J P 2012 Phys. Rev. Lett. 109 097205
[28] Chang L J, Onoda S, Su Y X, Kao Y J, Tsuei K D, Yasaki Y, Kakurai K and Martin R L 2012 Nat. Commun. 3 992
[29] Huang Y P, Chen G and Hermene M 2014 Phys. Rev. Lett. 112 167203
[30] Lee S B, Onoda S and Balents L 2012 Phys. Rev. B 86 104412
[31] Dun Z L, Trinh J, Li K, Lee M, Chen K W, Baumbach R, Hu Y F, Wang Y X, Choi E S, Shastry B S, Ramirez A P and Zhou H D 2016 Phys. Rev. Lett. 116 157201
[32] Ding Z F, Yang Y X, Zhang J, Tan C, Zhu Z, Chen G and Shi L 2018 arXiv:1802.00968 [cond-mat.str-el]
[33] Li Y S, Chen G, Tong W, Pi L, Liu J J, Yang Z R, Wang X Q and Zhang Q M 2015 Phys. Rev. Lett. 115 167205
[34] Li Y S, Adroja D, Biswas P K, Baker P J, Zhang Q, Liu J J, Tsirlin A A, Gegenwart P and Zhang Q M 2016 Phys. Rev. Lett. 117 097201
[35] Shen Y, Li Y D, Wu H L, Li Y S, Shen S D, Pan B Y, Wang Q S, Walker H C, Steffens P, Boehm M, Hao Y Q, Quintero-Castro D L, Harrier L W, Frontzek M D, Hao L J, Meng S Q, Zhang Q M, Chen G and Zhao J 2016 Nature 540 559
[36] Paddison J A M, Daum M, Dun Z L, Ehlers G, Liu Y H, Stone M B, Zhou H D and Mourigal M 2017 Nat. Phys. 13 117
[37] Xu Y, Zhang J, Li J S, Yu Y J, Hong X C, Zhang Q M and Li S Y 2016 Phys. Rev. Lett. 117 267202
[38] Zhang X S, Mahmood F, Daum M, Dun Z L, Paddison J A M, Laurita N J, Hong T, Zhou H D, Armitage N P and Mourigal M 2018 Phys. Rev. X 8 031001
[39] Li Y S, Adroja D, Bewley R I, Voneshen D, Tsirlin A A, Gegenwart P and Zhang Q M 2017 Phys. Rev. Lett. 118 107201
[40] Li Y S, Bachus S, TokiwaY, Tsirlin A A and Gegenwart P 2018 arXiv:1804.06966 [cond-mat.str-el]
[41] Li Y S, Adroja D, Voneshen D, Bewley R I, Zhang Q M, Tsirlin A A and Gegenwart P 2017 Nat. Commun. 8 15814
[42] Xu Z, Wang J H, Dong Z Y, Zhang J, Li S C, Zheng S H, Yu Y J, Wang W, Chen Q M and Zhao J 2016 Phys. Rev. Lett. 117 106413
[43] Shen Y, Li Y D, Walker H C, Steffens P, Boehm M, Zhang X W, Shen S D, Wu H L, Chen G and Li S Y 2017 arXiv:1708.06655 [cond-mat.str-el]
[44] Li Y D, Wang X Q and Chen G 2016 Phys. Rev. B 94 035107
[45] Li Y D, Wang X Q and Chen G 2016 Phys. Rev. B 94 134114
[46] Liu C L, Li Y D and Chen G 2018 Phys. Rev. B 98 045119
[47] Curnoe S H 2008 Phys. Rev. B 78 094418
[48] Onoda S and Tanaka Y 2011 Phys. Rev. B 83 094411
[49] Li Y D, Lu Y M and Chen G 2017 Phys. Rev. B 95 045445
[50] Parker E and Balents L 2018 Phys. Rev. B 97 184413
[51] Li Y D, Shun Y, Li Y S, Zhao J and Chen G 2018 Phys. Rev. B 97 125105
[52] Li Y D and Chen G 2017 Phys. Rev. B 96 075105
[53] Zhu Z Y, Maksimov P A, White S R and Chernyshev A L 2017 Phys. Rev. Lett. 119 157201
[54] Zhu Z Y, Maksimov P A, White S R and Chernyshev A L 2017 Phys. Rev. Lett. 120 077203
[55] Kimchi I, Nahum A and Senthil T 2018 Phys. Rev. X 8 031028
[56] Senthil T 2008 Phys. Rev. B 78 045109
[57] Baenitz M, Schleider P, Sichelschmidt J, Onyikienko Y A, Zhang Y, Ranjith K M, Sarkar R, Honozi L, Walker H C, Ojacin J C, Yasuoka H, van den Brink J, Klaus H H, Inosov D S and Doert S 2018 arXiv:1809.01947 [cond-mat.str-el]