Discovery of Fractionalized Neutral Spin-1/2 Excitation of Topological Order

Xiao-Gang Wen(文小刚)**

Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 31 July 2017)

PACS: 01.10.−m DOI: 10.1088/0256-307X/34/9/090101

After the discovery of fraction quantum Hall states in the 1980s,[1] it became more and more clear that Landau symmetry breaking theory does not describe all possible quantum phases of matter. The new quantum phases of matter were called topologically ordered phases[2,3] (for gapped cases) or quantum ordered phases[4] (for gapless cases), which correspond to patterns of many-body entanglement.[5−7] One may wonder: besides quantum Hall systems, are there other systems that realize the new topological/quantum order?

In the 1980s and 1990s, it was shown theoretically that topological orders can be realized in spin liquids, such as the chiral spin liquids[8,9] and Z_2-spin liquids.[10,11] Also, stable quantum ordered phases can be realized in algebraic spin liquids.[12−15] The topological/quantum ordered states are not easy to detect since they are not characterized by local order parameters. On the other hand, the absence of local order parameters lead to a strange way to discover topological/quantum ordered states: *one tries to detect any kind of order parameters and phases transitions as the temperature is lower to zero. If one finds nothing, then one can declare that a certain topological/quantum ordered state is discovered (if the trivial ground state can be ruled out).* In fact, such a strategy was used by Y. Lee, which led to a discovery of herbertsmithite as a possible spin liquid candidate on Kagome lattice.[16] A few years earlier, another spin liquid candidate was discovered in organic Mott insulator of triangular lattice.[17] The above two are 2-dimensional spin liquids. A 3-dimensional spin liquid candidate was found in hyperkagome antiferromagnet.[18] Recently, a very promising spin liquid was discovered in honeycomb lattice α-$RuCl_3$ with strong spin-orbital coupling.[19−25]

One of the most important properties of a spin liquid is whether the spin liquid is gapped or gapless. If the spin liquid is gapped, then the next important question is whether the spin liquid has fractionalized spin-1/2 quasiparticles or not. The appearance of spin-1/2 excitations implies a non-trivial topological order in the spin liquid. However, one challenge to study herbertsmithite in more detail is to reduce the influence of magnetic impurities. The 5–10% magnetic impurities in herbertsmithite make it difficult to determine if the spin liquid is gapped or gapless.[26] In a recent work, Ref. [27], published by Chinese Physics Letters, a new kind of Kagome spin liquid was found in a new material $Cu_3Zn(OH)_6FBr$. The new material allows one to measure Knight shift via ^{19}F NMR measurements (with $I = 1/2$ nuclear spin). The intrinsic Cu-spin magnetic susceptibility from Knight shift reveals a small spin gap of 8 K (compared to the spin coupling of 200 K). The small spin gap is consistent with a recent numerical calculation which found a long correlation length in the Heisenberg model on Kagome lattice.[28] Furthermore, the magnetic field dependence of spin gap indicates that the thermally excited spin excitations carry fractionalized spin-1/2.

Just like the direct discovery of fractional charge via noise measurement,[29] the discovery of a totally new fractionalized neutral spin-1/2 excitation is a very exciting result. This result suggests that the Kagome spin liquid is the Z_2-spin liquid with a Z_2 topological order.[10,11] The $SO(3)$ symmetric Z_2 topological order features emergent spin-1/2, emergent fermions, etc.[10,11] However, at moment, it is not clear whether the observed spin-1/2 excitation is a boson or a fermion. Hopefully, more detailed future experiments can resolve this issue. I also like to remark that the spin liquid in α-$RuCl_3$ does not have the $SO(3)$ spin rotation symmetry. In this case, it is harder to directly detect the fractionalization of topological order.

References

[1] Tsui D C, Stormer H L and Gossard A C 1982 *Phys. Rev. Lett.* **48** 1559
[2] Wen X G 1989 *Phys. Rev.* B **40** 7387
[3] Wen X G 1990 *Int. J. Mod. Phys.* B **4** 239
[4] Wen X G 2002 *Phys. Rev.* B **65** 165113
[5] Chen X, Gu Z C and Wen X G 2010 *Phys. Rev.* B **82** 155138
[6] Zeng B and Wen X G 2015 *Phys. Rev.* B **91** 125121
[7] Swingle B and McGreevy J 2016 *Phys. Rev.* B **93** 045127
[8] Kalmeyer V and Laughlin R B 1987 *Phys. Rev. Lett.* **59**

**Corresponding author. Email: xgwen@mit.edu

2095
[9] Wen X G, Wilczek F and Zee A 1989 *Phys. Rev.* B **39** 11413
[10] Read N and Sachdev S 1991 *Phys. Rev. Lett.* **66** 1773
[11] Wen X G 1991 *Phys. Rev.* B **44** 2664
[12] Affleck I and Marston J B 1988 *Phys. Rev.* B **37** 3774
[13] Rantner W and Wen X G 2001 *Phys. Rev. Lett.* **86** 3871
[14] Hermele M, Senthil T, Fisher M P A, Lee P A, Nagaosa N and Wen X G 2004 *Phys. Rev.* B **70** 214437
[15] Ran Y, Hermele M, Lee P A and Wen X G 2007 *Phys. Rev. Lett.* **98** 117205
[16] Helton J S, Matan K, Shores M P, Nytko E A, Bartlett B M, Yoshida Y, Takano Y, Suslov A, Qiu Y, Chung J H et al 2007 *Phys. Rev. Lett.* **98** 107204
[17] Shimizu Y, Miyagawa K, Kanoda K, Maesato M and Saito G 2003 *Phys. Rev. Lett.* **91** 107001
[18] Okamoto Y, Nohara M, Aruga-Katori H and Takagi H 2007 *Phys. Rev. Lett.* **99** 137207
[19] Banerjee A, Bridges C A, Yan J Q, Aczel A A, Li L, Stone M B, Granroth G E, Lumsden M D, Yiu Y, Knolle J et al 2016 *Nat. Mater.* **15** 733
[20] Baek S H, Do S H, Choi K Y, Kwon Y S, Wolter A U B, Nishimoto S, van den Brink J and Büchner B 2017 *Phys. Rev. Lett.* **119** 037201
[21] Zheng J, Ran K, Li T, Wang J, Wang P, Liu B, Liu Z, Normand B, Wen J and Yu W 2017 arXiv:1703.08474 [cond-mat.str-el]
[22] Hentrich R, Wolter A U B, Zotos X, Brenig W, Nowak D, Isaeva A, Doert T, Banerjee A, Lampen-Kelley P, Mandrus D G et al 2017 arXiv:1703.08623 [cond-mat.str-el]
[23] Wolter A U B, Corredor L T, Janssen L, Nenkov K, Schönecker S, Do S H, Choi K Y, Albrecht R, Hunger J, Doert T et al 2017 *Phys. Rev.* B **96** 041405
[24] Wang Z, Reschke S, Hüvonen D, Do S H, Choi K Y, Gensch M, Nage U, Rõõm T and Loidl A 2017 arXiv:1706.06157 [cond-mat.str-el]
[25] Jansa N, Zorko A, Gomilsek M, Pregelj M, Krämer K W, Biner D, Biffin A, Rüegg C and Klanjsek M 2017 arXiv:1706.08455 [cond-mat.str-el]
[26] Imai T, Fu M, Han T H and Lee Y S 2011 *Phys. Rev.* B **84** 020411
[27] Feng Z, Li Z, Meng X, Yi W, Wei Y, Zhang J, Wang Y C, Jiang W, Liu Z, Li S, Liu F, Luo J, Li S, Zheng G Q, Meng Z Y, Mei J W and Shi Y 2017 *Chin. Phys. Lett.* **34** 077502
[28] Mei J W, Chen J Y, He H and Wen X G 2017 *Phys. Rev.* B **95** 235107
[29] de Picciotto R, Reznikov M, Heiblum M, Umansky V, Bunin G and Mahalu D 1997 *Nature* **389** 162