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

Discovery of fractionalized neutral spin-1/2 excitation of topological order

Xiao-Gang Wen[1]

[1]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

After the discovery of fraction quantum Hall states in the 1980's[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: beside quantum Hall systems, are there other systems that realize the new topological/quantum order?

In the 1980's and 1990's, 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 8K (compare to the spin coupling of 200K). 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.

1 D. C. Tsui, H. L. Stormer, and A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1982).
2 X.-G. Wen, Phys. Rev. B **40**, 7387 (1989).
3 X.-G. Wen, Int. J. Mod. Phys. B **4**, 239 (1990).
4 X.-G. Wen, Phys. Rev. B **65**, 165113 (2002), cond-mat/0107071.
5 X. Chen, Z.-C. Gu, and X.-G. Wen, Phys. Rev. B **82**, 155138 (2010), arXiv:1004.3835.
6 B. Zeng and X.-G. Wen, Phys. Rev. B **91**, 125121 (2015), arXiv:1406.5090.
7 B. Swingle and J. McGreevy, Phys. Rev. B **93**, 045127 (2016), arXiv:1407.8203.
8 V. Kalmeyer and R. B. Laughlin, Phys. Rev. Lett. **59**, 2095 (1987).
9 X.-G. Wen, F. Wilczek, and A. Zee, Phys. Rev. B **39**, 11413 (1989).
10 N. Read and S. Sachdev, Phys. Rev. Lett. **66**, 1773 (1991).
11 X.-G. Wen, Phys. Rev. B **44**, 2664 (1991).
12 I. Affleck and J. B. Marston, Phys. Rev. B **37**, 3774 (1988).
13 W. Rantner and X.-G. Wen, Phys. Rev. Lett. **86**, 3871 (2001), cond-mat/0010378.
14 M. Hermele, T. Senthil, M. P. A. Fisher, P. A. Lee, N. Nagaosa, and X.-G. Wen, Phys. Rev. B **70**, 214437 (2004), cond-mat/0404751.
15 Y. Ran, M. Hermele, P. A. Lee, and X.-G. Wen (2006), cond-mat/0611414.
16 J. S. Helton, K. Matan, M. P. Shores, E. A. Nytko, B. M. Bartlett, Y. Yoshida, Y. Takano, A. Suslov, Y. Qiu, J.-H.

Chung, et al., Phys. Rev. Lett. **98**, 107204 (2007), cond-mat/0610539.

[17] Y. Shimizu, K. Miyagawa, K. Kanoda, M. Maesato, and G. Saito, Phys. Rev. Lett. **91**, 107001 (2003).

[18] Y. Okamoto, M. Nohara, H. Aruga-Katori, and H. Takagi, Physical Review Letters **99**, 137207 (2007), arXiv:0705.2821.

[19] A. Banerjee, C. A. Bridges, J.-Q. Yan, A. A. Aczel, L. Li, M. B. Stone, G. E. Granroth, M. D. Lumsden, Y. Yiu, J. Knolle, et al., Nature Materials **15**, 733 (2016), arXiv:1504.08037.

[20] 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, Phys. Rev. Lett. **119**, 037201 (2017), arXiv:1702.01671.

[21] J. Zheng, K. Ran, T. Li, J. Wang, P. Wang, B. Liu, Z. Liu, B. Normand, J. Wen, and W. Yu (2017), arXiv:1703.08474.

[22] R. Hentrich, A. U. B. Wolter, X. Zotos, W. Brenig, D. Nowak, A. Isaeva, T. Doert, A. Banerjee, P. Lampen-Kelley, D. G. Mandrus, et al. (2017), arXiv:1703.08623.

[23] A. U. B. Wolter, L. T. Corredor, L. Janssen, K. Nenkov, S. Schönecker, S.-H. Do, K.-Y. Choi, R. Albrecht, J. Hunger, T. Doert, et al., Phys. Rev. B **96**, 041405 (2017), arXiv:1704.03475.

[24] Z. Wang, S. Reschke, D. Hüvonen, S.-H. Do, K.-Y. Choi, M. Gensch, U. Nage, T. Rõõm, and A. Loidl (2017), arXiv:1706.06157.

[25] N. Jansa, A. Zorko, M. Gomilsek, M. Pregelj, K. W. Krämer, D. Biner, A. Biffin, C. Rüegg, and M. Klanjsek (2017), arXiv:1706.08455.

[26] T. Imai, M. Fu, T. H. Han, and Y. S. Lee, Phys. Rev. B **84**, 020411 (2011), arXiv:1103.2457.

[27] Z. Feng, Z. Li, X. Meng, W. Yi, Y. Wei, J. Zhang, Y.-C. Wang, W. Jiang, Z. Liu, S. Li, et al., Chinese Physics Letters **34**, 077502 (2017), arXiv:1702.01658.

[28] J.-W. Mei, J.-Y. Chen, H. He, and X.-G. Wen, Phys. Rev. B **95**, 235107 (2017), arXiv:160609639.

[29] R. de Picciotto, M. Reznikov, M. Heiblum, V. Umansky, G. Bunin, and D. Mahalu, Nature **389**, 162 (1997).