Graviton-like excitation observed with predicted chirality in fractional quantum Hall liquids

Kun Yang[1,*]

[1]Physics Department, Florida State University, Tallahassee, FL 32306, USA

*Correspondence: kunyang@magnet.fsu.edu

Received: April 1, 2024; Accepted: May 16, 2024; Published Online: May 18, 2024; https://doi.org/10.1016/j.xinn.2024.100641

Citation: Yang K. (2024). Graviton-like excitation observed with predicted chirality in fractional quantum Hall liquids. The Innovation **5(4)**, 100641.

Fractional quantum Hall liquids are the prototypical topological states of matter, whose universal topological properties are well understood in most cases (with few exceptions that will be discussed later). However, as emphasized by Duncan Haldane, who shared the 2016 Nobel Prize for his contribution to topological physics in condensed matter, purely topological descriptions of fractional quantum Hall liquids are incomplete because they overlook a geometrical aspect of the physics. Based on this insight, Haldane and his Princeton associates[1] argued that the long-wavelength collective excitations of fractional quantum Hall liquids correspond to oscillation of this geometry. In particular, the quantum of such oscillation carries spin angular momentum 2, very much like the gravitons in a putative quantum theory of gravity. For this reason, they use the same name ("graviton") for these geometric excitations.

Such graviton-like excitations were clearly seen in a detailed numerical study.[2] More importantly, this collaboration of Florida State University, Princeton, and California State University, Los Angeles,[2] demonstrated that these "gravitons" carry a definitive chirality (or angular momentum) that is either −2 or +2, depending on whether the fractional quantum Hall liquid is electron-like (−2) or hole-like (+2) (Figure 1). It also provided a detailed recipe on how to reveal the chirality in a Raman scattering experiment using circularly polarized light. Raman scattering is the ideal tool to excite these "gravitons" and detect their chirality because it is a two-photon process: an incoming photon gets absorbed by the system, which in turn emits another photon. The energy and spin of the "graviton" correspond to the energy and spin difference of the incoming and outgoing photon respectively. On the other hand, one-photon processes (which are more common in condensed matter experiments) cannot be used to excite such graviton-like excitations due to their angular momentum mismatch (a single photon carries spin-1C). In fact, Raman scattering was used by Aron Pinczuk and his Bell Lab collaborators to probe collective excitations of fractional quantum Hall liquids in the 1990s. Unfortunately, the old experiments used unpolarized light, making it impossible to extract the spin quantum number of these excitations, although the energy of the excitations detected was in good semi-quantitative agreement with the numerical results.[2] During a collaboration meeting in the fall of 2019, the authors[2] invited Pinczuk (who had since moved from Bell to Columbia University) to join them at Princeton, and they proposed to him using polarized light for his Raman experiment to reveal the graviton chirality. Acknowledging the challenge associated with it, Pinczuk was excited by this opportunity and started a project with his student Ziyu Liu to perform this experiment. Unfortunately, Pinczuk's effort at Columbia was slowed down by the ensuing pandemic, and it eventually stalled due to his untimely passing in 2022.

Fortunately, a group of former students, postdocs, and collaborators of Pinczuk, led by Lingjie Du (a former postdoc of his) of Nangjing University, carried the torch on. Using the more modern equipment available in Du's lab and samples grown by Pinczuk's former Bell Lab collaborators Loren Pfieffer and Ken West (now at Princeton), this team succeeded in performing the polarized Raman scattering in a number of prominent fractional quantum Hall liquids.[3] They find resonance peaks in the Raman spectra, only when the combinations of the polarizations of the incoming and outgoing light match the anticipated graviton chirality, in complete agreement with theoretical predictions.[2] This work[3] represents the discovery of graviton-like excitations in fractional quantum Hall liquids and their chiralities.

It is hard to overestimate the importance of the discoveries reported by Liang et al.[3] First of all, this is (most likely) the first time that a spin-2 (graviton-like) excitation is seen in nature. Elementary particles in nature are either spin-1/2 (like electron), spin-1 (like photon), both of which are seen routinely, or spin-0; the only known particle in the last category is the Higgs boson, which was discovered some twelve years ago (after decades of search). It is believed that elementary (or fundamental) gravitons must exist in the yet-to-be-found quantum theory of gravity, which are the quanta of gravitational waves (detected only nine years ago). Excitations in condensed matter systems often have particle-like characters, but they are really quanta of collective motions of underlying particles (mostly electrons); they are called quasiparticles instead. The graviton-like excitations discovered by Liang et al.[3] are such quasiparticles. Just like elementary particles, quasiparticles in condensed matter systems also mostly have spin-1/2 (like quasi-electrons and quasi-holes in a metal), spin-1 (like plasmons and polaritons), or spin-0 (like phonons in helium-4 liquid). Spin-2 or quadrupolar modes do exist, but they tend to be over-damped because they decay very quickly to other quasiparticles supported by the system, thus disqualifying them as sharp excitations (or quasiparticles). In fractional quantum Hall liquids, such "gravitons" become quite sharp because other quasiparticles are gapped, thus severely

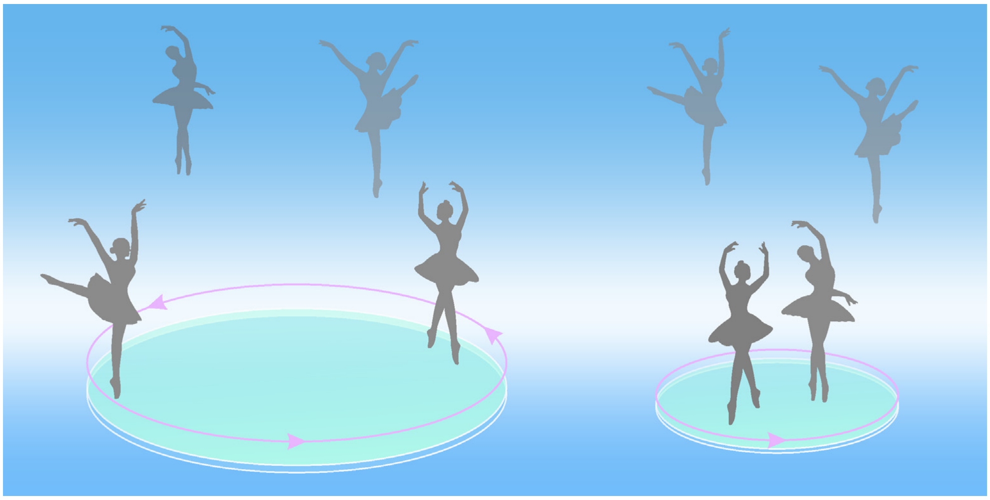

Figure 1. Illustration of graviton-like excitation and its chirality in the 1/3 Laughlin state using Xiao-Gang Wen's dancing pattern analogy Left panel: in the Laughlin ground state (or dancing pattern), the minimum relative angular momentum of a pair of dancers is three, ensuring sufficient separation between them. Right panel: a graviton-like excitation corresponds to a pair whose relative angular momentum changes from three to one (antisymmetry of fermion wave function only allows for odd relative angular momenta). This is not allowed in the Laughlin state, and as a result, it corresponds to an excitation that is the "graviton" detected by Liang et al.[3] In other words, the Raman process creates a "graviton" by turning a pair with relative angular momentum three (left panel) to a pair with relative angular momentum one (right panel). The angular momentum of this excitation is 1 − 3 = −2, corresponding to graviton chirality −2. For hole states like 2/3, because the chirality is reversed for holes, graviton chirality becomes +2.

limiting the possible decay channels into them. This renders these "gravitons" clearly visible in the experiment.[3]

Secondly, these experiments[3] open the door for an entirely new way to study the topological properties of fractional quantum Hall liquids. Traditionally such topological properties are probed at the edge, through the so-called bulk-edge correspondence. Unfortunately, there are various complications at the edge that are incompletely understood, which make the interpretation of edge experiments hard or ambiguous in many cases. The Raman scattering experiment,[3] on the other hand, is a purely bulk probe that is *not* subject to such complications. In particular, it was proposed[4,5] that one can use the graviton chirality to pin down the precise topological order of the fractional quantum Hall liquid at Landau level filling factor 5/2, which is the most interesting state at present, not only because there are multiple candidate states (thus it is important to find out which one is actually realized), but also the leading candidates are non-Abelian with potential applications in topological quantum computation. Thus, future experiments like the one performed by Liang et al.[3] may lead to the discovery of certain non-Abelian states of matter.

Lastly, this type of work facilitates dialogue and synergy among different fields of physics. Admittedly, the "gravitons" here are quite different from the real gravitons in a quantum theory of gravity. The obvious differences are as follows: (1) here, we have two instead of three (or higher) spatial dimensions in quantum gravity. (2) The geometry behind the quantum Hall "gravitons" is purely spatial, while that of Einstein's theory of general relativity (the quantum version of which is quantum gravity) is for space-time. (3) Perhaps most importantly, these quantum Hall "gravitons" are gapped, while those of quantum gravity must be gapless so that the gravitational force is long ranged. There is, however, enough similarity between them that both communities should be strongly interested in the developments of the other. As discussed by Liang et al.,[3] the "gravitons" discovered there are quite similar to some historical proposals of massive gravitons in the context of gravity theory, especially those in two spatial dimensions.

REFERENCES

1. Yang, B., Hu, Z.-X., Papić, Z., et al. (2012). Model wave functions for the collective modes and the magnetoroton theory of the fractional quantum hall effect. Phys. Rev. Lett. ***108***: 256807. https://doi.org/10.1103/PhysRevLett.108.256807.
2. Liou, S.-F., Haldane, F.D.M., Yang, K., et al. (2019). Chiral gravitons in fractional quantum hall liquids. Phys. Rev. Lett. ***123***: 146801. https://doi.org/10.1103/PhysRevLett.123.146801.
3. Liang, J., Liu, Z., Yang, Z., et al. (2024). Evidence for chiral graviton modes in fractional quantum Hall liquids. Nature ***628***: 78–83.
4. Haldane, F.D.M., Rezayi, E.H., and Yang, K. (2021). Graviton chirality and topological order in the half-filled landau level. Phys. Rev. B ***104***: L121106. https://doi.org/10.1103/PhysRevB.104.L121106.
5. Nguyen, D.X., and Son, D.T. (2021). Probing the spin structure of the fractional quantum Hall magnetoroton with polarized Raman scattering. Phys. Rev. Res. ***3***: 023040. https://doi.org/10.1103/PhysRevResearch.3.023040.

ACKNOWLEDGMENTS

This work is supported by the National Science Foundation grant DMR-2315954.

DECLARATION OF INTERESTS

The author declares no competing interests.