Journal Club for Condensed Matter Physics DOI:10.36471/JCCM_March_2023_01
https://www.condmatjclub.org

A cold atom realization of coherent and incoherent Tomonaga-Luttinger liquids

1. **Spin-charge separation in a one-dimensional Fermi gas with tunable interactions**
   Authors: Ruwan Senaratne, Danyel Cavazos-Cavazos, Sheng Wang, Feng He, Ya-Ting Chang, Aashish Kafle, Han Pu, Xi-Wen Guan, Randall G. Hulet
   Science **376**, 1305 (2022); arXiv:2111.11545
2. **Realization of a spin-incoherent Luttinger liquid**
   Authors: Danyel Cavazos-Cavazos, Ruwan Senaratne, Aashish Kafle, and Randall G. Hulet
   arXiv:2210.06306

Recommended with a Commentary by Thierry Giamarchi, University of Geneva

One dimensional quantum systems have a set of remarkable properties, quite different from their higher dimensional counterparts. Indeed in one dimension any interaction will transform the motion of an individual particle into a collective excitation and these collective excitations (sound modes) of charge or of spin exhaust all the possibilities of excitation. As was shown by Haldane, [1, 2] the low energy properties of such systems are described by a universal set of properties (the so called Tomonaga-Luttinger liquid (TLL)). Among its defining properties [3] one has: i) nonuniversal power-law decay of correlation functions, with interaction dependent exponents; ii) fractionalization of *elementary local* excitations – such as removing an electron or flipping a spin – into *collective and non-local* excitations. For example a particle carrying charge and spin (a quasiparticle in higher dimensions) can fractionalize into an excitation carrying a charge and no spin (the holon) and one carrying spin but no charge (the spinons). This fractionalization has important physical consequences such as continuum spectra and naturally topological excitations.

It is thus extremely interesting to check experimentally this physics. Observation of power-laws has been readily done in several condensed matter systems [3]. Observing the fractionalization is however much more challenging given the non-local nature of the objects. In condensed matter realizations the relatively poor control on the microscopic hamiltonian also makes quantitative comparisons with theoretical predictions based on idealized models such as the Hubbard model difficult. As a result examples are scarce and to the best of my knowledge the most solid evidence is provided by a tunnelling experiment between quantum wires [4] showing the indirect effects of two different velocities on the tunnelling.

Given the offered level of control and tunability it was thus natural to hunt for the spin-charge separation in cold atomic systems. Such systems allow the direct realization of idealized models with contact interactions such as the Hubbard model and allow to control on the value of the interaction [5, 6]. They can thus serve as quantum simulators to test for this physics. Using fermions trapped on an optical lattice the group of I. Bloch observed, by monitoring the density of each spin species on each site [7], the separation in real space and time of the spinon and the holon when one particle is removed from a 1D chains. Although the size of the system is still relatively short (about 12 sites) this provided a very strong experimental evidence of the spin-charge separation.

The two papers mentioned in this commentary, follow a different and complementary route. They deal with continuous and relatively long systems. The fermions interact by a contact interaction. This model, known as the Gaudin-Yang model, is also exactly solvable by Bethe-ansatz (BA) [8]. It thus provides an excellent analytical knowledge of the the charge and spin velocities as a function of the strength of the interaction.

Both papers use the so-called Bragg spectroscopy to probe the system, It is in short the equivalent of both X-ray and neutron scattering depending on whether the symmetric or antisymmetric combination of densities is probed (see Fig. 1 of paper 1). It measures essentially the imaginary part of the retarded density-density (or spin density- spin density) correlation function [9]. Given the fact that we expect in 1D those to be dominated by a collective mode of velocity u_ν, the response is of the form $\overline{\delta}(\omega - u_\nu q)$ where $\overline{\delta}$ is a broadened δ function (with a very precise lineshape on which I will come back below). Measurement of the peak (see Fig. 2 of paper 1), at fixed q thus gives the velocity of the two collective modes of charge and spins for different values of the interaction.

Fig. 2 of paper 1 shows that indeed these velocities are different and moreover that their dependence in the interaction follows very well what is expected for the Gaudin-Yang model. This is of course a remarkable result. It not only shows the expected spin-charge separation in a TLL, but also that the experimental system indeed acts as a usable quantum simulator of the Gaudin-Yang model. This opens the door to using it in situations where the theory is much less well established. This is the task of paper 2.

Before moving to paper 2, let me add a couple of comments on the measurements performed in paper 1:

1. In principle one could also test for the lineshape of the peak whose form is non trivial. However in this system the lineshape is blurred by the average over many tubes with different densities. This is the consequence of the existence of a parabolic confinement trap. The position of the peak is also affected, but fortunately the system is controlled well enough so that reconstructing the position in a single tube with a fixed density can be made. Needless to say equivalent measurements in a box potential would simplify considerably the procedure and give access to the additional physics of the lineshape. This is of course a major experimental challenge.

2. Although the lineshape could not be analyzed, the tails at large q could be analyzed. This goes beyond TLL and uses the exact BA solution. The good agreement between theory and experiment confirms the accuracy with which the microscopic model is implemented experimentally.

3. Stricto sensu, seeing two collective modes with different velocities is not *directly* checking the spin-charge separation, which could only be probed through the single particle spectral function, or its real time-space equivalent. However given the *demonstrated* 1D nature of the system we know that the two collective modes exhaust all the excitations and that spin-charge separation *does* exist if the two velocities of charge and spin are different. The quantitative measurement of these two velocities is thus in my opinion a very strong experimental proof. It will of course in the future be interesting to see if one could probe the single particle spectral function as was done in other cold atoms systems.

4. Last but not least the temperature is still the enemy here since T/T_F is typically quite high in "cold" fermionic gases. This is however less damaging in such continuum systems than if an optical lattice is used to reduce the kinetic energy. So having continuous and long systems as in the two mentioned papers is certainly a very interesting feature.

In paper 2 this simulator is used to explore a very interesting regime of the TLL , namely the so-called incoherent TLL. Indeed as was shown by Cheianov and Zvonarev [10] using BA and then by Feite and Balents [11] with field theory there can exists, a regime in which the spin excitations have an energy lower than the temperature T (on a lattice that would correspond to $T \gg t^2/U$ where t is the tunnelling, but where the charge is perfectly coherent since the temperature is smaller than the typical charge energy (on a lattice that would be $T < t$ and $T < U$). In such a regime the spin-spin correlation decay exponentially so one cannot analyze the system in terms of the two collective modes spinons and holons with two different velocities any more and the analysis is quite involved (see e.g. the review [12]) and a quantum simulator is useful to complement the analytical and numerical analyzes of this regime.

Paper 2 establishes the experimental existence of such a regime in the Gaudin-Yang model with a temperature raising from $T = 500$ nK to above the charge scale and with two energy scales of 630 nK for the spin and 1330 nK for the charge. The measure of the peak is similar to the one of paper 1. It shows convincingly that in the spin incoherent regime the symmetric and antisymmetric peaks coincide (see Fig. 3 of paper 2 showing that the position of the peaks collapse in this regime). Both density-density and spin density-spin density correlation are dominated by the charge mode since the spin mode is incoherent.

This is an excellent and very promising use of the simulator. It tackles a question which is considerably more complicated to analyze than the low temperature coherent regime. For the moment there is no detailed comparison with theoretical formulas. This is after all what you would expect from a successful quantum simulator whose purpose is to provide an answer where the other theoretical methods cannot (yet) go.

These results will most certainly stimulate intensive theoretical efforts to analyze and reproduce the experimental results.

References

[1] F. D. M. Haldane, J. Phys. C **14**, 2585 (1981).

[2] F. D. M. Haldane, Physical Review Letters **45**, 1358 (1980).

[3] T. Giamarchi, *Quantum Physics in One Dimension*, Vol. 121 of *International Series of Monographs on Physics* (Oxford University Press, Oxford, 2004).

[4] O. M. Auslaender *et al.*, Science **308**, 88 (2005).

[5] I. Bloch, J. Dalibard, and W. Zwerger, Reviews of Modern Physics **80**, 885 (2008).

[6] T. Esslinger, Annual Review of Condensed Matter Physics **1**, 129 (2010).

[7] J. Vijayan *et al.*, Science **367**, 186 (2020).

[8] M. Gaudin, *La Fonction d'onde de Bethe* (Masson, Paris, 1983).

[9] T. L. Yang *et al.*, Physical Review Letters **121**, 103001 (2018).

[10] V. V. Cheianov and M. B. Zvonarev, Physical Review Letters **92**, 176401 (2004).

[11] G. A. Fiete and L. Balents, Physical Review Letters **93**, 226401 (2004).

[12] G. A. Fiete, Reviews of Modern Physics **79**, 801 (2007).