QSS24 - Federica Surace, Gal Ness, Martin Ringbauer - Questions & Answers

Federica Surace, Gal Ness, Martin Ringbauer

Table of Contents

1. Federica Surace

It's really nice to see the possibility to realise this particular lattice gauge theory in experiments. Could you say more about which classes of lattice gauge theories we already know how to implement in expeirment, and how close we are to the theories you mentioned at the beginning (that arise, e.g., for frustrated magnets or in high energy physics?) Or, which ingredients might we need to add in order to realise those classes of lattice gauge theory?

FEDERICA: So far, experiments have been able to simulate lattice gauge theories in 1+1 dimensions, with U(1) gauge symmetry. For more complicated theories, some ideas for implementation have been proposed, but not yet realized: the big challenge is simulating theories with non-Abelian gauge symmetries and in higher dimensions. These steps are fundamental if we want to reach the level of complexity needed for studying problems of interest in theoretical physics (for example the open questions in quantum chromodynamics).

We heard a few seminars ago that these models for Rydberg atoms exhibit "quantum many-body scars" for initial states, with very robust oscillations. Do these have direct analogies in your lattice gauge theories?

FEDERICA: The robust oscillations associated with quantum many-body scars have a clear explanation in the gauge theory counterpart. The lattice gauge theory that we map to the Rydberg Hamiltonian is a lattice version of the Schwinger model, a theory for quantum electrodynamics in one spatial dimension. In the continuum limit, the Schwinger model can be mapped to a free scalar bosonic field theory. The oscillations observed in the experiment correspond to the excitation of a single bosonic mode with zero momentum in the field theory. Therefore, the oscillations in the continuum limit of the gauge theory are exact and do not decay in time.

Rydberg atoms can be easily created in two-dimensional arrays. Do your ideas regarding gauge fields generalize to two dimensions?

FEDERICA: Although our mapping does not straightforwardly generalize to two dimensions, the general approach that we use, based on the integration of matter degrees of freedom, can be applied also in two dimensions. We are now working on this generalization, which requires using both s and p Rydberg states for implementing orientation-dependent interactions.

Bill Phillips: What is important about Ry atoms for simulating dynamic gauge fields that is absent in, for example, contact interactions? Is it between contact and longer range interactions?

FEDERICA: In our mapping, long range interactions are not crucial. The most important ingredient is the presence of different energy scales (in this case: the Rabi frequency and the

nearest-neighbour Rydberg interaction), which result in a constrained dynamics. Another key advantage of using Rydberg atoms is the possibility of designing space-dependent detunings: this allows, in our scheme, for the manipulation of the theta-angle, a parameter which controls the confining-deconfining nature of the theory.

2. Gal Ness

Bill Phillips: Given that the BCS-BEC transition is smooth, why does one expect (at least initially) the polaron-molecule transition to be sharp?

GAL: In the single impurity at zero temperature limit, various theoretical calculations indicate that the energies of the polaron and molecule ground states as a function of the interaction cross with a finite relative slope. It was also shown that both states maintained as stable excitations in interactions for which they are not the ground state, as the phase-space for decay vanishes linearly with the energy difference. Therefore, both states are reachable as metastable states when approached from the regime where they are lower, as expected for a first-order transition. The BCS-BEC transition features a smooth crossover where the pair correlation transforms continuously from momentum to distance pairing. However, in the polaron-to-molecule transition case, particularly in the single impurity limit, the overlap between the two ground states vanishes. Therefore, we do not expect an "intermediate" state as the unitarity gas is for the BCS-BEC crossover. This qualitative difference between the balanced and the completely-imbalanced cases is precisely what makes the phase-diagram regime we studied, strong imbalance yet of finite impurity density, so interesting.

Bill Phillips: Is it obvious that the mass of the polaron is a well-defined constant, and that it remains the same in a momentum-transferring Raman transition?

GAL: The polaron is a well-defined quasiparticle as we find a narrow branch in the spectral function even when it is not the ground state. Its effective mass can be extracted from the dispersion's curvature, thus it is also well defined. However, it varies with the interaction strength and therefore is not a constant. The effective mass is conventionally defined by the curvature of the dispersion at zero momentum. One can generalize the effective mass concept also to finite momenta. Interestingly, even for a given interaction, we theoretically find a non-parabolic behavior of the dispersion, and therefore anticipate a momentum-dependent effective mass. After the transition, the final state of the outcoupled atoms (F=9/2, mf=-5/2) is almost non-interacting with the other states; thus, the outcoupled atoms can be well approximated by free particles, characterized by the bare mass. Therefore, the effective mass changes during the transition. To precisely extract the effective mass at zero and finite momentum, one can either use injection spectroscopy to introduce an impurity at a specific momentum, or implement some hybrid scheme that probes both the particle's momentum and energy.

If you generalize to repulsive polarons, can you model just this in the same way and apply the same experimental techniques, or are there particular complications in that case? What do you expect to see there?

GAL: The repulsive polaron state is not the ground state of the system, and it is characterized by a finite lifetime. Therefore, dynamics play a central role in both the experimental and theoretical treatment of its study. Our theoretical model can also describe the repulsive polaron state, as it appears in the calculated spectral functions. However, extensions have to be made to capture its dynamics. Experimentally, the main challenge is creating these polarons and probing them on a timescale that is much shorter than their lifetime. We expect to measure a spectral peak at lower detunings, correlative to their higher energy. Also in the repulsive polaron case, the Raman spectrum directly reflects its momentum distribution and offers a shift-free tool to extract their zero-momentum energy.

I do not understand what you did to get the high sensitivity. Could you say a bit more about that?

Was it better imaging?

GAL: We use selective fluorescence imaging of the outcoupled atoms to gain the high-sensitivity feature of our probing technique. To this end, we drive a microwave adiabatic-rapid-passage to transfer these atoms into a state in another hyperfine manifold of potassium 40 (F=7/2, mf=-3/2), which is magnetically trappable, in contrast to all other involved states. So, using a magnetic trap, we selectively keep only the transferred atoms. Then, we turn on MOT beams and capture the fluorescence light from these atoms, which provides a highly sensitive signal.

3. Martin Ringbauer

Every community and even research group seems to have their own way of comparing quantum devices so that their own looks particularly good. Can you say a bit more about what the most "fair" comparison is? Is your's fair?

MARTIN: It is indeed not trivial to design a benchmark that does not play into the advantages of one or the other platform. However, our goal here is not to benchmark quantum devices, but rather cross-check them to build trust in their output. We do this by randomly sampling from different circuits on at least two devices to establish whether these two devices give consistent results. It would be counterproductive for this goal to play into advantages of a certain platform and the method also cannot even provide a quantitative estimate for a single device.

Bill Phillips: Have I understood correctly that you have a method for checking a circuit-based quantum computer that uses insight gained from thinking about a measurement-based quantum computer?

MARTIN: This is correct. We use MBQC as the underlying framework to establish a "hidden" connection between two distinct and random-looking circuits to cross-check circuit-based quantum computers. One can even think of it as starting from a circuit, then deriving the corresponding MBQC and from there a second circuit to do the cross-check with.

You've talked about how these measurements scale with the size of the Hilbert space. Is there also an important dependence of the relative error on how large the distance between the distributions is? I.e., is this method better/worse for detection when the devices are very close or very different?

MARTIN: The method is inherently agnostic about the underlying probability distribution. However, scaling gets better for peaked distributions and worse for flat distributions. Hence, devices that have a lot of depolarizing noise will require more samples to obtain an estimate for the squared l^2 norm.