Four-dimensional quantum walks on an optical quasicrystal

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Ultracold atoms in optical lattices (OLs) are a powerful tool for simulating a variety of condensed-matter systems, allowing us to create designer potentials via the light shift by interfering off-resonant laser beams. Our group has constructed the first-ever such experiment to simulate a two-dimensional quasicrystal, a state of matter with long-range order but no translational symmetry. We achieve this by superimposing four mutually incoherent one-dimensional OLs at 45° angles, creating a pattern with eightfold rotational symmetry that by the crystallographic restriction theorem cannot be periodic. By exposing a BEC of ^{87}Rb to brief pulses of lattice light lasting a few µs and imaging in time of flight, we can observe this lattice in momentum space (see Fig. 1).

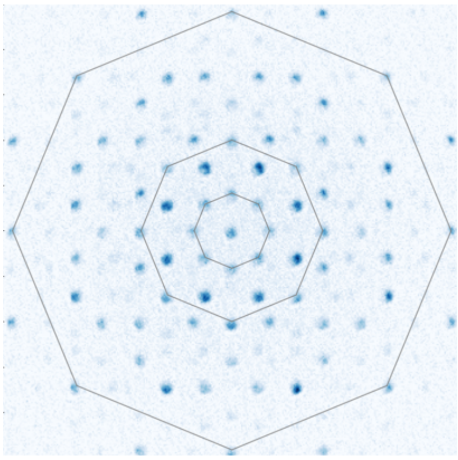

Fig. 1: Raw time-of-flight image of a BEC exposed to a 6 µs pulse of the quasicrystal lattice. This eightfold-symmetric pattern corresponds to the structure factor of the lattice. By varying the pulse duration we can observe the BEC spreading in momentum space, which simulates a quantum random walk in four dimensions. The octagons illustrate the self-similarity of the quasicrystal, which repeats itself infinitely on ever-larger lengthscales.

The irrational value of sin(45°) results in two lengthscales along each axis: 1 and $\frac{\sqrt{2}}{2}$. This requires each point to be indexed with a total of four integers, corresponding to the number of momentum kicks along each of the four lattice beams, and this in turn means that the pattern simulates a four-dimensional simple-cubic crystal. This provides a powerful and flexible experimental platform, as the dimensionality reduces by one for each laser we switch off: we can repeat the same experiments in one, two, three and four dimensions.

So far we have worked in momentum space to see how our BEC spreads out to new diffraction peaks with increasing pulse length, simulating a quantum random walk (equivalent to classical ballistic expansion). We plan to upgrade our experiment to work with ^{39}K (bosonic) in the near future and ^{40}K (fermionic) after that, allowing us to repeat these measurements without interactions by taking advantage of Feshbach resonances.

In addition we are interested in the real-space physics of the quasicrystal, especially relating to transport. By altering the power in two of the four lattice beams we can tune continuously between the periodic and quasiperiodic limits, which will allow us to chart a two-dimensional phase diagram in interaction energy U and quasidisorder Δ (as has been done by D'Errico et al for a one-dimensional quasicrystal [1]). We expect to observe Bose glass and Mott insulating phases, and many-body localisation at higher energies.

References

[1] C D'Errico et al, Phys. Rev. Lett. 113, 095301, August 2014

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