MRI for a quantum simulation

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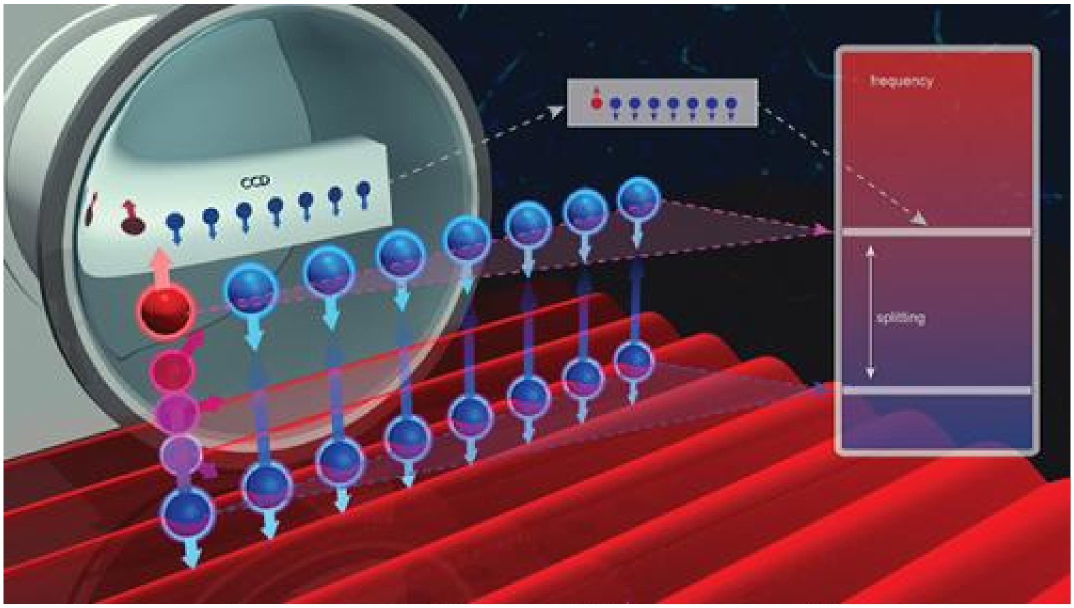

A probe (shown here as a red wave) is scanned until it resonantly excites spins in the crystal. Excitation is shown as a single spin flip. A site-resolving imaging objective collects fluorescence from the chain. CCD images are used to determine properties of the system such as an energy level diagram. Credit S. Kelley/JQI

Magnetic resonance imaging (MRI), which is the medical application of nuclear magnetic resonance spectroscopy, is a powerful diagnostic tool. MRI works by resonantly exciting hydrogen atoms and measuring the relaxation time—different materials return to equilibrium at different rates; this is how contrast develops (i.e. between soft and hard tissue). By comparing the measurements to a known spectrum of relaxation times, medical professionals can determine whether the imaged tissue is muscle, bone, or even a cancerous growth. At its heart, MRI operates by quantum principles, and the underlying spectroscopic techniques translate to other quantum systems.

Recently physicists at the Joint Quantum Institute* led by JQI Fellow Christopher Monroe have executed an MRI-like diagnostic on a crystal of interacting quantum spins. The technique reveals many features of their system, such as the spin-spin interaction strengths and the energies of various spin configurations. The protocol was published recently in the journal *Science*. Previously, such methods existed for an array of only three spins—here, the JQI team performed proof-of-principle experiments with up to 18 spins. They predict that their method is scalable and may be useful for validating experiments with much larger ensembles of interacting spins.

'Spin' models are a vital mathematical representation of numerous physical phenomena including magnetism. Here, the team implements an Ising spin model, which has two central features. The spins themselves have only two options for orientation ("up" or "down"), and the interactions happen between pairs of spins, much like the interaction between bar magnets. The Ising model can be generalized to many seemingly disparate systems where there are binary choices. For instance, this model was used to study how ideas spread through social networks. In this application, spin-spin interactions represented connections between people in a network, analogous to interaction energies between magnetic spins. Here, the extent of the human connection affected how opinions spread through a social network population.

Back in the quantum laboratory, physicists have the ability to precisely study and calculate everything about a single or a small collection of essentially "textbook" spin particles within various physical platforms.

Yet gaining a complete understanding of the behavior of many interacting spins is a daunting task, for both experimentalists and theorists. Ion traps are a leader in experimental studies of quantum physics, and thus well-poised for tackling this challenge.

The sheer numbers involved in large spin systems give insight into the difficulty of studying them. Consider that for N number of particles there are N(N-1)/2 two-body interactions. The interactions give rise to an energy spectrum containing 2N individual spin configurations. Here, the team does a complete analysis with 5 spins, and so there are 10 two-body interactions and 32 different spin chain configurations. Conventional computers can work with these modest numbers, but for as few as 30 spins the number of states pushes past a billion, which begins to be prohibitively complicated, particularly when the 435 separate interactions are all distinct. Physicists hope that quantum simulators can help bridge this gap.

The Ion Trap Quantum Spin Simulator

Quantum Simulation is a term that broadly describes the use of one controllable quantum system to study a second analogous, but less experimentally feasible quantum phenomenon. A full-scale quantum computer does not yet exist and classical computers often cannot solve large-scale quantum problems, thus a "quantum simulator" presents an attractive alternative for gaining insight into complex problems.

In the experiment described here, laser-cooled ytterbium atoms confined inside an ion trap are configured to simulate an array of spins. Each spin is made from two of the ion's internal energy levels that are separated by a microwave frequency of 12.642819 GHz (billion vibrations/second). When radiation having this frequency interacts with the ion, its spin flip-flops between the two spin states, "up" and "down".

The ions also have a vibrational frequency determined by the trap that confines them—typically around 1 MHz or 1 million vibrations/second. In the quantum regime, the quanta of vibration called a phonon can be controllably added and removed from the system with precisely controlled external laser forces. These phonons act as communication channels for the spins, and when combined with the gigahertz radiation, are used to generate a rich variety of interactions.

The simulation begins with the spins initialized into a well-known spin configuration (e.g. all of the spins in the "up" configuration). Then, the physicists apply a probe, which is a tiny oscillating electromagnetic field generated from the laser. They scan this probe to find the special "resonant" frequencies that cause the spin crystal to undergo transitions to different configurations (see Figure 1 in gallery). This energy/frequency is directly related to how the spins are interacting with each other. If the spins are interacting weakly, with only their nearest neighbors, then the transition energy will be different than when the interactions are more extended. To assemble a complete energy spectrum and measure all configurations the team must repeatedly probe the ion spins over a range of frequencies. A crucial component of this protocol is the imaging system, which allows the team to directly measure each individual ion spin in the crystal for every probe frequency.

The JQI team hopes this new tool will ease the way towards simulating larger systems and possibly other spin models. Says Crystal Senko, JQI graduate student and lead author of this work, "Quantum simulation experiments will eventually be studying physics questions that can't be answered in any other way, so we might not know how to tell if the experiment isn't doing quite what we expected. That means it will be important to have many diagnostics, so that when we see something strange and interesting we can be confident that it's interesting physics instead of just a bug in the experiment."

Significantly, this protocol is not limited to trapped ions, and can be tailored to different simulation platforms. Just as MRI is an indispensable tool in modern medicine, this new verification technique may prove essential to the realm of quantum simulation.

More information: "Coherent imaging spectroscopy of a quantum many-body spin system," C. Senko, J. Smith, P. Richerme, A. Lee, W.C. Campbell, C. Monroe, *Science*, 345, 430 (2014). DOI: 10.1126/science.1251422

Provided by Joint Quantum Institute

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