tracts can be constrained, which might make it easier to avoid the limitations of current algorithms and to validate different tracking techniques (across scales, across subjects, across species, etc.).

A common view that arises from the studies of both Chen *et al*. and Wedeen *et al*. is the idea of the brain as a regionally highly differentiated, but hierarchically and geometrically organized, spatial structure. Detailed aspects of this "canonical brain organization" can be modified by environmental conditions including pathology and genetic diversity. Mathematical methods such as hierarchical clustering and differential geometry can help us to understand the principles behind variable phenotypes and to guide the development of a realistic brain model.

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PHYSICS

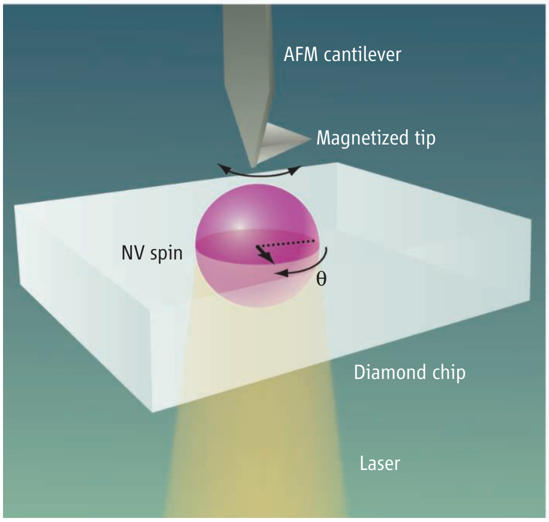
A Single Spin Feels the Vibrations

Philipp Treutlein

The vibrations of a cantilever with a magnetic tip can be detected by changes in the electronic spin state of a defect embedded in a nearby diamond surface.

Mechanical resonators find widespread applications as precision force sensors, the most prominent example being the atomic force microscope (AFM). Coupling the vibrations of a mechanical resonator to a fully controlled, microscopic quantum system such as a single spin presents a strategy for detecting and even controlling mechanical vibrations in the quantum regime. The resulting hybrid quantum system would offer new perspectives for precision force sensing and tests of quantum mechanics on a macroscopic scale. On page 1603 of this issue, Kolkowitz *et al*. (*1*) have taken a first step toward such coupled spin-resonator systems by using a single electronic spin to sense mechanical vibrations of an AFM cantilever with a magnetic tip.

Observing and manipulating quantum behavior of mechanical objects is a goal currently being pursued through several different experimental approaches (*2*). Although quantum-level control over mechanical vibrations is routinely achieved for atomic-scale objects such as trapped ultracold atoms and ions (*3*), achieving a similar level of control over microstructured mechanical resonators such as cantilevers, beams, and membranes is far more challenging. Observing quantum behavior with a mechanical resonator that is visible to the naked eye, such as an AFM cantilever, would not only be a beautiful confirmation of quantum theory but may also lead to novel applications in precision force sensing (*4*).



Spin flips in sync with vibrations. A single spin in a diamond crystal can be used to read out the vibrations of an AFM cantilever. The magnetized cantilever tip induces a coupling between the cantilever vibrations and the spin resulting in a spin rotation by an angle θ. The quantum state of the spin is subsequently detected with a laser.

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In order to observe quantum behavior, the resonator must be cooled to sufficiently low temperatures to avoid thermally excited vibrations. Equally important, tools are needed to read out the resonator and to determine and possibly even control its quantum state. One strategy is to couple the mechanical resonator to a microscopic quantum system, ideally a single two-level system (a "qubit") that can be fully controlled quantum mechanically and can be read out efficiently. In a recent landmark experiment (*5*), a superconducting phase qubit was coupled to an internal mechanical vibration of a piezoelectric resonator at millikelvin temperatures and used for preparation and detection of nonclassical quantum states. The coherence lifetimes of the qubit and resonator quantum states were in the nanosecond range, and it is desirable to achieve similar control in other systems with longer coherence lifetimes. Moreover, from a standpoint of applications in force sensing, it is important to achieve quantum-level control over the fundamental center-of-mass vibration of a cantilever resonator, as used in an AFM. A number of different qubit-cantilever systems are currently being investigated for this purpose, involving systems from solid-state physics (*6*) as well as ultracold atoms and ions (*7*).

The spin of a single nitrogen vacancy (NV) center in diamond—the qubit system used by Kolkowitz *et al*.—is very promising. Its quantum state can be initialized and read out optically, it can be manipulated by applying microwave radiation, and it shows remarkably long coherence times—up to a few milliseconds even at room temperature (*8*). The spin can be coupled to the vibrations of a cantilever (*9*) by attaching a tiny magnet to the cantilever tip and positioning it near the diamond surface (see the figure). The strong magnetic field gradient that is produced translates the vibrations of the cantilever into an oscillating magnetic field, which couples

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to the NV spin via its magnetic moment. The resulting change of the spin's quantum state can be detected optically.

The interaction of a single spin and a mechanical resonator has already been studied from a somewhat different perspective: Using an ultrasensitive mechanical cantilever with a magnetic tip, researchers detected single electron spins embedded in a solid material (*10*), a technique known as magnetic resonance force microscopy. The experiment of Kolkowitz *et al*. turns this situation around and uses the spin to sense mechanical vibrations. During the measurement, the quantum state of the spin is controlled by microwave radiation. A clever sequence of coherent manipulation pulses is applied to the spin in orde r to enhance its sensitivity to the vibrations while suppressing noise from other sources. In this way, Kolkowitz *et al*. sense mechanical vibrations down to a few picometers in amplitude.

In a previous experiment on spin-resonator coupling, Arcizet *et al*. coupled an NV spin to the vibrations of a SiC nanowire (*11*). The NV was fixed to the tip of the nanowire while the magnet was placed near to it. They observed nanowire vibrations of a few tens of nanometers in amplitude through a change in the line shape of the NV spin resonance. Kolkowitz *et al*. used the coherent quantum dynamics of the NV spin to reach higher sensitivity to mechanical vibrations.

The resonator motion detected here is in the classical regime at room temperature, but with the magnetic coupling mechanism, it is in principle possible to reach the quantum regime (*6*). Several technological improvements are necessary to reach this goal, including fabrication of a smaller cantilever with a much higher mechanical quality factor and a magnet made from a different material, and working at cryogenic temperatures. Ultimately, the system will have to reach the so-called strong-coupling regime, where the excitation of a single quantum of vibration (a single phonon) in the resonator is sufficient to flip the spin, and a single spin flip is sufficient to excite vibrations of the resonator. In this regime, the system realizes a mechanical analog of current experiments in cavity quantum electrodynamics (*12*), where the internal state of a single atom is strongly coupled to a single quantum of the electromagnetic field (a photon) inside an optical cavity.

A strongly coupled spin-resonator system in the quantum regime bears some analogy with the infamous Schrödinger's cat: The microscopic spin could be prepared in a quantum mechanical superposition state of pointing up and down at the same time. It could then influence the macroscopic mechanical cantilever (playing the role of the cat) so that the cantilever ends up in a superposition state of vibrating in two opposite directions at once. Although some caution is in order—the cantilever contains a macroscopic number of atoms, but a superposition state involving only a few phonons is still in some sense microscopic—such an experiment would certainly be intriguing. From an applied perspective, the use of a single spin, the most elementary quantum system, to read out mechanical vibrations opens the path to force detectors operating at the ultimate limits of sensitivity. The experiment of Kolkowitz *et al*. is an exciting first step in this direction.

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GEOCHEMISTRY

Keeping Time with Earth's Heaviest Element

New ^{238}U/^{235}U ratios for uranium-bearing minerals provide a better chronometer for dating geological processes.

Claudine H. Stirling

Uranium is the heaviest naturally occurring element on Earth. It has three natural isotopes (^{238}U, ^{235}U, and ^{234}U), of which ^{238}U and ^{235}U are the parent nuclides of the ^{238}U- and ^{235}U-decay series chains, which ultimately decay to stable isotopes of lead (Pb), thereby forming the basis of the U-Pb chronometer. Conventional theories of stable isotope fractionation have dictated that uranium is too heavy to display resolvable mass-dependent isotope effects. The expectation was that Earth would display homogeneous ^{238}U/^{235}U isotopic compositions. The convention has been to adopt an invariant present-day ^{238}U/^{235}U ratio equal to 137.88 throughout the solar system, on the basis of early studies of uranium ore deposits. This critical assumption, which underpinned the veracity of the U-Pb chronometer for the past 30 years, was overturned by the discovery of surprisingly large ^{238}U/^{235}U variations in Earth's surface environments (*1*, *2*). On page 1610 of this issue, Hiess *et al*. (*3*) report the ^{238}U/^{235}U composition of a large suite of U-bearing accessory minerals to facilitate a more accurate U-Pb geochronometer. These new results also provide fundamental but unexpected insights into the mechanisms controlling ^{238}U/^{235}U fractionation.

Together with the other actinides, uranium was produced over the lifetime of the galaxy in massive exploding stars (supernovae) and was then incorporated into Earth during the formation of the solar system more than 4.5 billion years ago. In the past decade, high-precision measurements of ^{238}U/^{235}U were initially driven by the search for the former existence of extinct ^{247}Cm (*4*, *5*), the short-lived precursor nuclide of ^{235}U. ^{247}Cm is a crucial actinide for evaluating models of solar system formation and is detected as small positive anomalies in the ^{238}U/^{235}U ratio of extraterrestrial meteorites (*6*). Contrary to expectations, initial measurements of ^{238}U/^{235}U in terrestrial reference materials revealed surprisingly large isotopic variability of approximately 1 per mil (‰) in a wide range of low-temperature environments (*1*, *2*). These isotopic shifts

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