Quantum Mechanics Tackles Mechanics

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lation to human may not always be direct. For instance, Hoxb4 converts blood precursors from mouse ESCs into HSC-like cells (*11*), yet extensive efforts to adapt HOXB4 for human cells have been largely unsuccessful (*12*). The advent of powerful genome-editing technologies enables the creation of transgenic human lines harboring defined factors or stem cell reporters. Combined with improved xenotransplantation models, engineering directly in human cells with functional validation in engrafted mice is an attractive approach.

Moving forward, the stem cell research community must creatively apply directed differentiation and direct conversion toward engineering clinically valuable cells, targeting the generation of either mature functional cells or stem cells, depending on the anticipated clinical application and guided by the cell type and tissue of interest. For long-lived cells such as cardiomyocytes and neurons, integration of mature cells into the tissue remains a viable option. Still, the stem cell approach should be explored, because functional tissue integration may be more permissive for neural or cardiac progenitors. For short-lived tissues such as blood, mesenchyme, skin, or intestinal epithelium, the generation of somatic stem cells will be a prerequisite for stable engraftment and prolonged tissue reconstitution. Such advances will require novel markers and reporter lines, deeper understanding of stem cell–specific transcription factors, and screening strategies formulated to derive and detect rare stem cells. The fundamental demonstration of the past decade that cell identity can be molded to our specifications has created an unprecedented opportunity to create rare patient-specific cell types and even tissues. The decade to come will establish whether this revolution in basic science will have a lasting impact on medicine.

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PHYSICS

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A micromechanical oscillator can only be described with quantum mechanics after it is entangled with microwave fields.

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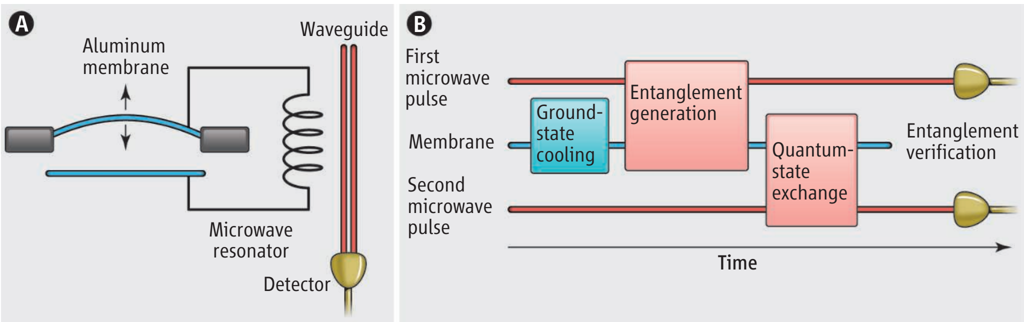
Quantum theory describes the physical cosmos at atomic and smaller scales, but can we apply quantum mechanics to large, distributed mechanical structures? Several recent experiments have shown that we can observe quantum dynamics of nano- and micromechanical oscillators. On page 710 of this issue, Palomaki *et al.* (*1*) report the controlled generation and verification of quantum entanglement of a mesoscopic mechanical device (a mechanical oscillator) with an electromagnetic microwave field. Entanglement is considered to be the distinguishing feature that separates quantum from classical physics. Only the properties of the entire system have precise values, and the mechanical resonator and the microwave field must be described by one compound quantum-mechanical wave function. No such wave functions can be assigned to either of the subsystems separately.



Massive entanglement. (**A**) The experimental setup of Palomaki *et al*. used a vibrating micrometer-sized aluminum membrane integrated in a microwave resonator. The resonator was driven through an adjacent waveguide. The amplitudes of fields emanating from the microwave cavity were detected. (**B**) The protocol for entanglement generation and verification is illustrated: The membrane mechanical oscillator was initialized in its quantum-mechanical ground state. An initial pulse became entangled with the oscillator, and the quantum state of the oscillator was swapped to a second pulse. The train of two pulses was detected, and the entanglement was verified from the cross correlation of the subsequent measurements.

In the experiment performed by Palomaki *et al*., a thin circular aluminum membrane (100-nm thick and 15 mm in diameter) was suspended in a fixed frame and was free to oscillate like a drumhead. The fundamental mode of this mechanical oscillator is the one that became entangled with the microwave field. The aluminum also served as one end of a parallel plate capacitor that was integrated into a resonant circuit with a characteristic frequency in the microwave domain at a frequency of $2\pi \times 8$ GHz (see the figure, panel A). The mechanical motion of the drum mode changed the capacitance and with it the resonance frequency of the microwave cavity. This mechanism resulted in an extremely strong mutual coupling between the mechanical and the microwave resonator.

The coupling happened on a time scale faster than the characteristic time scale on which quantum states of the two resonators could be destroyed by uncontrolled interactions with their respective environments. At the experimental temperature of 20 mK, the

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coherence of quantum states could be preserved up to times on the order of hundreds of microseconds, well beyond the time scale of the strong mutual coupling of the mechanical oscillator and the microwave resonator.

In addition to the large strength of coupling, the authors also exploited its rich controllability: By driving the resonator circuit with microwave fields of suitable frequency, they could select one out of a number of different effects induced by the coupling: When the driving field had a frequency below the resonance of the microwave cavity, the net effect was to cool the mechanical resonator. Even the quantum mechanical ground state could be reached with this method. The cooling process can be regarded also as a swap between the thermal state of the mechanical oscillator and the quantum state of the incoming microwave field in vacuum. Both processes, cooling to the mechanical ground state and coherent state exchange between the mechanical oscillator and the microwave field, have been demonstrated separately in the same laboratory with a similar system (*2*, *3*).

When the driving field was tuned above the cavity frequency, the opposite effect prevailed, and both systems were heated up. However, the blurring of the properties of the subsystems and their seeming thermalization are just facets of the entanglement generated between the motion of the mechanical oscillator and the microwave field. Far from being thermally excited, the state of the compound system had almost zero entropy. It was actually very close to the famous entangled state introduced almost 80 years ago by Einstein, Podolsky, and Rosen in their discussion of the ostensible incompleteness of quantum mechanics (*4*).

Palomaki *et al*. combined all of these tools for quantum state engineering in a protocol (*5*) that proceeded in three steps (see the figure, panel B). They first cooled the mechanical oscillator to its ground state. The driving field was then swept above the resonance frequency to create an entangled state between motion and the microwave field. The entangled field left the cavity in the form of a short pulse and was guided to a detector where the field amplitudes were measured. Finally, after a short delay, the state of the mechanical oscillator was swapped to another pulse of the microwave field that was again guided to the detector. From the subsequent measurements of the two pulses emanating from the microwave cavity, the authors obtained complete information about the quantum state. They could precisely track how the properties of each of the subsystems became increasingly uncertain while the overall state stayed pure and exhibited strong correlations. Thus, the distinguishing quantum property of entanglement was observed in a system with a large mechanical degree of freedom.

The accomplishment by Palomaki *et al*. should be seen in the context of a series of other experiments that have tested and demonstrated implications of quantum theory in systems of micrometer-sized mechanical oscillators coupled to microwave or optical fields. Beyond ground state cooling (*2*, *6*) and coherent state exchange (*3*, *7*), optomechanical systems have also been used to observe slow light (*8*, *9*) and to verify some decade-old predictions of quantum measurement theory (*10*), namely, the generation of ponderomotive squeezing of light (*11*, *12*) and the occurrence of measurement back action noise in linear position sensing (*13*, *14*). These experiments, together with the newly observed optomechanical entanglement, finally achieve what has been formulated as a vision by Schwab and Roukes (*15*); they have put mechanics into quantum mechanics. It appears as if quantum theory, bizarre as it is, applies at any physical scale. It might just be getting dramatically more difficult to unveil it as we enter the truly macroscopic regime, but who knows how far we can go?

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PHYSICS

Cold-Atom Thermoelectrics

Two coupled reservoirs of cold atoms can be used as a model system to study the thermoelectric effect.

Tero T. Heikkilä

Thermoelectric devices can convert temperature differences into electric power, or cool materials by passing currents. On page 713 of this issue, Brantut *et al*. (*1*) demonstrate this kind of coupling between particle and heat currents in a laser-controlled cloud of lithium atoms. The precise control of such cold-atom systems allows for an accurate tuning of the thermoelectric effects that is usually not possible in solid-state systems. Such model systems will provide a testing ground for ideas aimed at improving thermoelectric devices.

Passing a current through an electric conductor heats it up due to its inherent resistance to the current. Under suitable conditions, a small current can also create a temperature difference across a contact between two conductors, so that one part cools down and the other heats up. This Peltier effect (*2*) is typically weak but is used in electricity-powered portable coolers. The reciprocal effect, electrical power generation from temperature differences, the Seebeck effect (*3*), occurs when two dissimilar conductors are connected in a loop and exposed to a temperature gradient. This thermopower is used especially in temperature sensors. If the efficiency of thermoelectric generation can be improved, then it could find application in power generation by harvesting the waste heat from various industrial processes. Thermoelectric effects have also found uses in various other applications, ranging from car-seat coolers and heaters to powering space missions (*4*).

The microscopic theory of the Peltier and Seebeck effects in metals and semiconductors has been understood for decades (*5*). However, the problem is that thermoelectric

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