or include Indigenous knowledge only superficially. To ethically bridge knowledge systems, meaningful engagement with knowledge holders is necessary at all stages, from project design to data interpretation and project evaluation (*10*, *13*).

To move from anecdote to the data that will be used by decision-makers, documentation of local knowledge must follow rigorous qualitative research design, including repeatable and transparent methods ("need to meet scientific credibility") (*5*, *9*). Identification of expert knowledge holders, thematic saturation and triangulation (qualitative research methods used to avoid missing and to corroborate information, respectively), and validation and cointerpretation of results will ensure accurate accounts, interpreted and applied in context, and will serve as an internal peer review process (*5*).

Through participatory appraisal exercises (such as mapping, timelines, and proportional piling), qualitative information from resource users can be translated into spatial, temporal, and numerical representations ("into categories/criteria that rely on numbers") (*5*). These types of data enable inclusion of local knowledge into familiar formats used for management decisions. As with scientific data, quantifying local observations allows us to understand variability around observations and act with knowledge of that uncertainty. However, qualitative and quantitative data must be documented and interpreted together to avoid misinterpreting information and loss of deeper insights.

Growing efforts to incorporate local knowledge into quantitative models [such as Bayesian Belief Networks (*14*)] can provide tools that further facilitate inclusion of this knowledge into decision-making. However, sophisticated mathematical models can pose technical barriers to participation, producing power imbalances (*15*). When applying these tools, it is paramount to ensure that Indigenous knowledge holders actively participate at all stages and share control of the process.

Inevitably, at times, Indigenous and scientific knowledges will conflict. Partners then need to coevaluate the strengths and limitations of the respective studies and jointly reflect on disparate findings. Such a contention arose in 1977 between scientists and indigenous whalers around the number of bowhead whales, which resulted in a hunting ban (*10*). This conflict was resolved only when the knowledge of Iñupiat whalers on bowhead whale behavior was considered, leading scientists to realize that they had severely underestimated the stock size based on faulty assumptions. This example is a reminder that such instances of conflict are opportunities for the greatest insights into ecological processes to be revealed, transformative knowledge generated, and improved dialogue among partners achieved, enabling the development of shared solutions.

"Don't shoot the leaders" echoes as a call for action to enable today's elders to pass their knowledge to the youth who will be tomorrow's leaders. The creation of an inclusive platform for knowledge exchange around wildlife health, a theme so central to many Indigenous cultures, improves wildlife conservation and public health protection, promotes intergenerational learning and retention of Indigenous knowledge within contemporary contexts, and contributes to reconciliation with Indigenous peoples. Respecting Indigenous knowledge and working collaboratively with knowledge holders will build capacity and empower Indigenous communities to set their own agendas as advocated by the United Nations (*7*). The latest report by the Intergovernmental Panel on Climate Change (IPCC) highlights the rate at which climate change is affecting the Arctic and other regions of the world (*2*), emphasizing the urgency with which we all need to embrace the concept of Etuaptmumk, to cogenerate knowledge and to learn from each other "for the benefit of all." ■

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SUPPLEMENTARY MATERIALS

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METROLOGY

Squeezing out higher precision

Well-timed kicks to an ion's momentum enable better position measurements

By **Monika Schleier-Smith**

Making measurements at a precision limited only by quantum uncertainty is crucial for applications such as the detection of gravitational waves (*1*) or the search for dark matter (*2*). In this quest, physicists can reduce uncertainty in measurements of one variable at the expense of another (*3*, *4*). Ultimately, however, the precision is often limited by the classical noise of the measurement apparatus. In principle, a solution to this problem is to amplify the signal relative to the classical noise. Readers familiar with cassette tapes may recognize this strategy, which is much like turning up the volume of music in a car so that it can be heard above the engine noise, only to have the tape hiss obscure the finer features of the music. On page 1163 of this issue, Burd *et al.* (*5*) report extremely sensitive measurements of the position of an individual ion, achieved by both suppressing quantum noise and amplifying signal.

Trapped ions are exquisitely well-controlled quantum systems, used as ultraprecise clocks (*6*) and as building blocks for quantum computers (*7*, *8*). Electric fields can be used to suspend a single ion in ultrahigh vacuum, and lasers are then used to bring it to rest in its lowest energy state. Even in this stable resting state, the ion has zero-point energy associated with quantum fluctuations in its position and momentum. In the case of the low-mass magnesium atom studied by Burd *et al.*, the motion created by the zero-point energy is 70 times the size of the ion in its trapped ground state. Does this mean that precise measurements of its position are futile?

The limit imposed by the Heisenberg Uncertainty Principle makes knowing both an object's position and its momentum at

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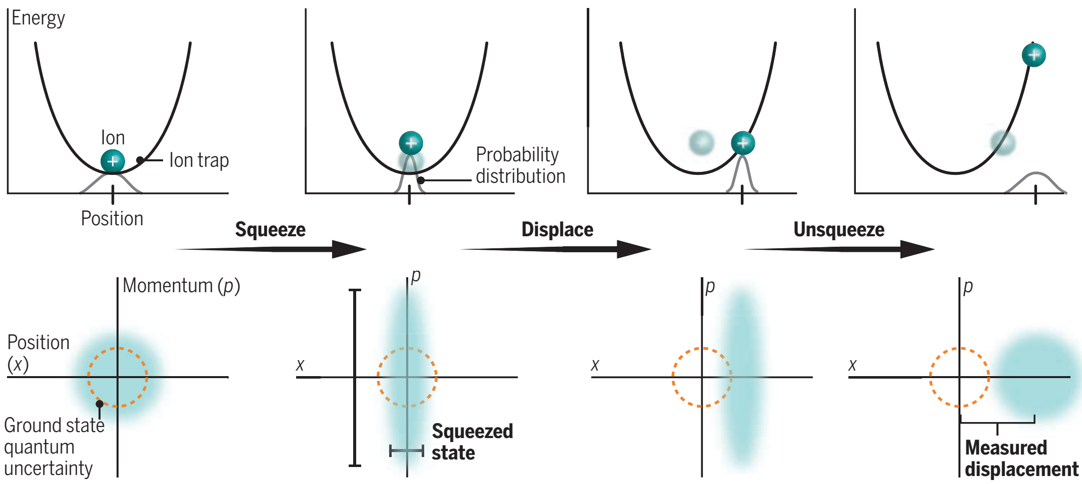
the same time impossible. However, we can know the position alone to arbitrary precision. When the imprecision becomes smaller than the quantum uncertainty of the resting state, the result is called a squeezed state. Squeezing the uncertainty in position requires hiding all information about the object's momentum, which in turn requires pumping in energy. The energy must, however, be added carefully to avoid just heating the ion up and increasing the uncertainties in both momentum and position.

Improving sensitivity to small displacements

Carefully manipulating the quantum fluctuations in an ion's motion improves the measurement precision.



The trapped ion is in its lowest energy state with an uncertainty in position and momentum (blue circle) set by quantum mechanics.

The energy of the ion is increased by modulating the electric field, which increases uncertainty in momentum but decreases it in position below the quantum limit.

The ion is displaced while in the squeezed state.

Amplifying the displacement returns the original quantum uncertainty, and both are now larger than the measurement error.

GRAPHIC: N. DESAI/*SCIENCE*

The ideal way to pump in energy, it turns out, is known to every child who has sat on a swing and pumped her legs. Imagine that the child starts out sitting as still as she can, like an ion at rest in its trap. Her position nonetheless might be ever so slightly perturbed from equilibrium, depending on the direction of the latest gust of wind. If she now starts to pump her legs, she can amplify that slight impulse. A distant observer who was unable to discern the size or direction of the initial perturbation will nonetheless easily see the amplified motion with each pump of the child's legs. Burd *et al.* achieve the same effect by modulating the electric fields that trap the ion, relaxing and tightening its confinement in the same rhythm as the child extending and compressing her legs.

You may recall from your own childhood that the timing of this rhythm is crucial, to avoid inadvertently slowing yourself down. Specifically, depending on exactly when you extend and contract your legs, you can amplify either your initial momentum or your initial displacement, but not both, as the other will be attenuated. Hence, Burd *et al.*'s amplification of the initial quantum fluctuations in momentum at the same time attenuates the quantum fluctuations in position, which places the ion into a squeezed state (see the figure). At a later time during the experiment, the same pumping trick amplifies a perturbation of the ion's motion, which is the signal that the experimenters wish to precisely measure. In amplifying the signal, they also amplify the quantum noise back to its original unsqueezed level. As a result, even with a measurement apparatus that can barely resolve the quantum noise of the initial state, the complete protocol can detect much smaller displacements, down to the level of the squeezed uncertainty.

This principle of amplified quantum sensing has been used to enhance optical interferometers (*9*) and has been demonstrated in atomic clocks and sensors whose signals are stored in internal states of an ensemble of many atoms (*10–12*). Its application to detecting tiny displacements of a single particle, however, required surmounting different technical challenges. The authors showed amplification of the quantum motion without adding any appreciable extra noise. In other words, they pumped energy into the system without heating it. They detected a displacement of less than 1 nm, which is smaller than the initial quantum uncertainty in the ion's position by a factor of 7.

The study by Burd *et al.* is an important milestone in advancing toward ultimate quantum limits in precision measurement and opens the door to several applications. One prospect is to make ions even better at what they already do best, which is precision spectroscopy. For example, by comparing the absorption spectra of different ionic species, it is possible to address fundamental questions such as whether the constants of nature are really constant. One method of measuring these spectra is notable for being applicable to a wide range of different ions and relies on detecting the tiny momentum kick imparted when an ion absorbs a photon (*13*). Quantum squeezing and amplification can make this method of photon recoil spectroscopy even more precise.

Extended to groups of multiple ions, noiseless amplification can enhance interactions that allow for transmitting quantum information between the ions (*14*) and may thus ultimately find applications in quantum computing. Another exciting prospect is to precisely detect the motion of increasingly massive objects that can be cooled to the quantum regime (*15*). A grand challenge is to detect minute gravitational forces in a regime where quantum mechanics simultaneously plays a role. Every bit of extra precision that can be squeezed from such systems will be essential to achieving that goal. ■

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