Research Highlight

Putting the squeeze on phonons

Photon squeezing has been the subject of intense interest in the field of quantum optics, since it serves as a unique demonstration of the quantum nature of light. On a practical level, squeezing offers opportunities to make interferometric measurements much more precise than would normally be allowed by quantum uncertainty limits [1]. In principle, the physics of squeezing may be applied to many different types of bosons. Our work demonstrates *phonon* squeezing by using femtosecond laser excitation of bismuth to create squeezed phonon states and then femtosecond x-ray diffraction to watch how the atomic position variance in the crystal evolves in time.

Squeezing is a phenomenon that can be observed in systems described by a simple harmonic oscillator [2]. Squeezing of the ground state of such an oscillator is depicted in Figure 1. If the system is initially in a time-independent eigenstate (or admixture of eigenstates), a sudden decrease in the frequency of the harmonic oscillator potential will "squeeze" the position-space distribution of the oscillator and launch oscillations in the expectation value of the variance of the position. In the case of phonons, this means that the deviation of the atoms in a crystal from their average positions will oscillate in time.

In an experiment reported in *Physical Review Letters*, we have used a femtosecond laser to generate squeezed phonons in a crystal of bismuth by exciting the electrons that hold the atoms in place. The excitation causes a weakening of the interatomic bonds, which in turn leads to a sudden decrease in the frequencies of phonons throughout the Brillouin zone. Because the atoms do not have time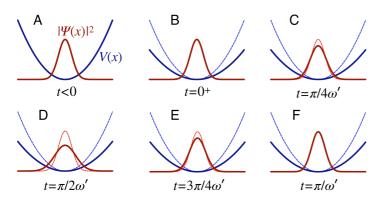 to move in response to this softening, immediately after the laser excitation they are "squeezed" into a tighter position-space distribution than the phonon frequencies would normally allow in an equilibrated thermodynamic state.

Figure 1: *Position-space probability distribution dynamics for the squeezed ground state of a simple harmonic oscillator. (A) Initially, the probability distribution corresponds to the ground state of the Hamiltonian with a parabolic potential $V(x) = m\omega^2 x^2$. (B) At a time $t = 0$ the frequency of the oscillator suddenly changes to a smaller value: $\omega \rightarrow \omega'$. Now the wavefunction is no longer an eigenstate of the Hamiltonian, and the width of the probability distribution in position space is "squeezed" to a smaller value than the width of the ground state probability distribution for the new, softened potential. (C-F) The wavefunction evolves in time, resulting in an oscillation in the width of the probability distribution with (angular) frequency $2\omega'$. Similar oscillations occur for other eigenstates of the initial potential.*

To watch how the atoms respond to the squeezing, we use femtosecond x-ray diffraction from the SLS electron beam slicing source [3] to look at the variance of the atomic positions relative to the average positions that they would take in a perfect crystal. This variance causes a decrease in the magnitude of diffraction via the Debye-Waller factor. Figure 2 shows the time-resolved atomic position

variance measured at one diffraction peak at room temperature. We see an increase along with a very quickly damped oscillation, corresponding to the sum of squeezing oscillations from many different phonon modes throughout the Brillouin zone. The data agree with a simple model of squeezing where we assume that all the phonon modes are softened by the same fractional amount.

This work demonstrates how the rapid injection of energy into the electronic states of a solid can lead to behavior that differs qualitatively from what can be understood with models based on treating the lattice as a system in thermodynamic equilibrium. By using x-ray diffraction to watch how atoms move as energy flows from the one subsystem to another we obtain unique insights into the nature of how different components of a solid interact.
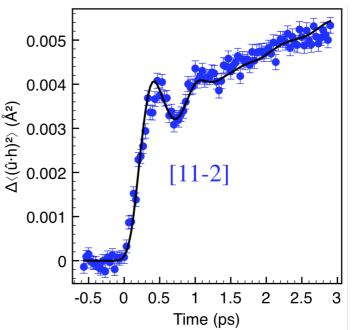

Figure 2: *Time-dependence of the atomic position variance after laser excitation. The electronic excitation from a femtosecond laser pulse at t = 0 suddenly decreases the frequencies of phonon modes in the crystal, creating squeezed phonon states. This causes oscillations in the measured deviation of atoms from their average positions. The solid line shows a fit to a simple model of phonon squeezing.*

References

[1] C. M. Caves et al. *Rev. Mod. Phys.* **52** 341-92 (1980).
[2] V. V. Dodonov. *J. Opt. B: Quantum Semiclass. Opt.* **4** R1-R33 (2002).
[3] P. Beaud et al. *Phys. Rev. Lett.* **99** 174801 (2007).

Publications

- **Directly Observing Squeezed Phonon States with Femtosecond X-Ray Diffraction**
  S. L. Johnson*, P. Beaud, E. Vorobeva, C. J. Milne, É. D. Murray, S. Fahy and G. Ingold
  Physical Review Letters **102**, 175503 (2009)
  doi:10.1103/PhysRevLett.102.175503

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