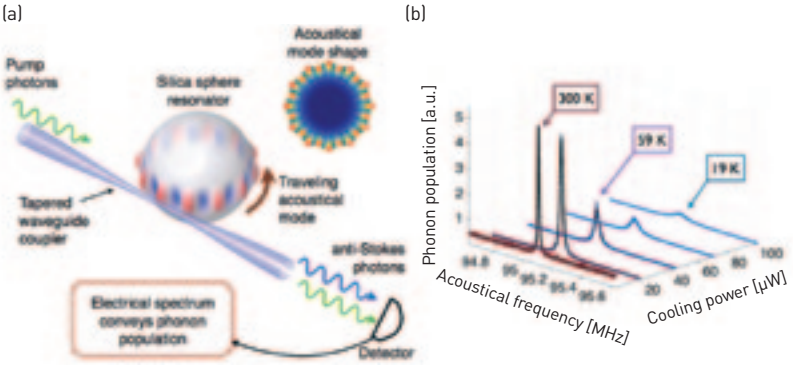
OPTICAL COOLING

Experimental Observation of **Spontaneous Brillouin Cooling**

Researchers can optically cool solids at the scale of individual atoms with fluorescence techniques, and the vibrations of entire devices with optomechanical techniques.[1,2] Our team developed a cooling method for the intermediate regime between atomic and device scale. This technique allows us to cool collective atomic motion in the form of acoustical waves by inverting the energy flow in the Brillouin scattering light-sound interaction.[3] In such interactions, incident photons are scattered to redder (Stokes) or bluer (anti-Stokes) frequencies, while heating or cooling the medium as required by energy conservation. It was thought that this cooling-heating balance is always tilted towards heating as governed by Planck distribution,[4] which is indeed true in bulk media where all photons are almost equally transmitted.

Brillouin cooling can be used in ultra-high Q optical microcavities, which allows selective resonant enhancement of the cooling anti-Stokes transition while rejecting the Stokes transition. In 2009, scientists achieved Brillouin Stokes scattering in such whispering gallery mode (WGM) optical resonators along with exciting 11-17 GHz vibrations.[5] However, phonons at these frequencies suffer from short lifetimes that preclude their ability to be cooled, since the relatively long-lived anti-Stokes photons can generate more phonons by scattering back to Stokes frequencies.

Our work showed that reversing the spatial scattering direction from back-scattering to forward-scattering enables access to lower frequencies where the acoustical Q (or phonon lifetime) is high. We measured an acoustical Q of 12,300 for a 95 MHz mode, bringing the Brillouin interaction into a regime where cooling is possible in accordance with the phonon-photon lifetime requirement.[3]



(a) Light is coupled in and out of the optical WGMs by a waveguide. Phonons are removed from the acoustical WGM by the anti-Stokes Brillouin scattering process, resulting in cooling. The beat note between pump and anti-Stokes photons provides phonon population measurement. (b) Phonon population decreases as a function of the input optical power. Linewidth broadening and the total area of the phonon population spectra are convenient measures of effective temperature of the acoustical mode.

Our experiment was based on a spherical fused-silica resonator with ultra-high optical Q of about 10^8 pumped at 1.5 μm. The device supports two optical WGMs and an acoustical WGM phase-matched to facilitate Brillouin scattering. The optical modes enhance cooling (anti-Stokes scattering) when the lower energy mode is pumped. This photon scattering removes phonons from the acoustical mode, broadening the acoustic linewidth, which helps to infer temperature.

Contrary to the belief that nonlinearity is enhanced with increasing pump power, the amount of scattered light decreases due to the waning Brownian phonon population. By measuring scattering from the thermal Brownian fluctuations, Brillouin scattering was shown to cool an acoustical mode from room temperature to 19 K with only 100 μW input power. OPN

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OPTICAL COOLING

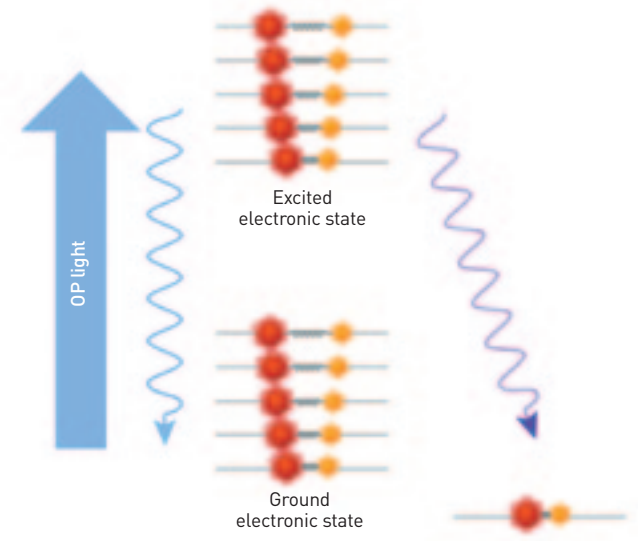
Lumino-Refrigeration: Deep Cooling Polar Molecules by Optical Pumping

Our ability to laser cool atoms depends on the availability of a closed-cycling transition that allows many successive photons to be scattered by the atom. By comparison, molecules have a richer internal structure that is an asset and a liability. It offers new degrees of freedom for exciting experiments but precludes a simple scheme for molecular laser cooling.

Kinetically cold (T < 1 mK) polar molecules in the rovibrational ground state are the starting point for investigating novel quantum states related to high-Tc superconductors, tests of time reversal symmetry, quantum computation and more.[1] The most successful approaches for creating the sample start by building molecules from ultracold atomic gasses. Current methods are either simple but inefficient or efficient yet technically challenging. Old methods used "pump-and-dump" in RbCs to transfer a small population into $X^1\Sigma^+(v = 0)$. Subsequently, direct photoassociation into $X^1\Sigma^+(v = 0)$ was observed for LiCs and NaCs; however, the sample was contaminated by molecules in other vibrational states. More recently, the JILA group demonstrated an elegant method in KRb involving magnetoassociation followed by coherent transfer to $X^1\Sigma^+(v = 0)$ using a sophisticated frequency comb reference.

Earlier this year, we showed vibrational cooling of NaCs molecules to $X^1\Sigma^+(v = 0)$ using a simple diode laser-based method via optical pumping.[2] The approach, called "lumino-refrigeration," was conceived by A. Kastler to describe the optical pumping (OP) of sodium atoms between hyperfine states.[3] The sample is cooled when the final (dark) state is at a lower energy than the initial state. OP plays a key role in laser cooling atoms and has been adapted to produce samples of ground-state Cs_2 molecules and molecular ions.

Electronic ground-state NaCs molecules at a T value of about 250 μK were first formed by photoassociation from laser-cooled and trapped gases of Na and Cs atoms. Photoassociation is an optically mediated chemical reaction in which a colliding pair of atoms is bound into an excited state molecule that then decays radiatively, forming a bound ground-state molecule.



Optical pumping pathways in NaCs. Ground-state molecules are pumped through the $A^1\Sigma^+ - b^3\Pi$ complex using broadband light that is not energetic enough to drive molecules out of $X^1\Sigma^+(v = 0)$. Excited state molecules decay to the ground state and population in $X^1\Sigma^+(v = 0)$ accumulates.

The resulting molecules spectroscopically included a wide range of vibrational states in the singlet and triplet ground state wells. Using a set of inexpensive laser diodes, we engineered an OP excitation spectrum by temperature tuning the lasers. The spectrum was selected such that the pumping light would excite the population in the initial distribution of levels allowing it to decay into the $X^1\Sigma^+(v = 0)$ state.

We showed that the process is capable of generating in excess of 10^5 molecules/s. This lumino-refrigeration should be generalizable to other bialkali polar molecules. OPN

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OPTICAL COOLING

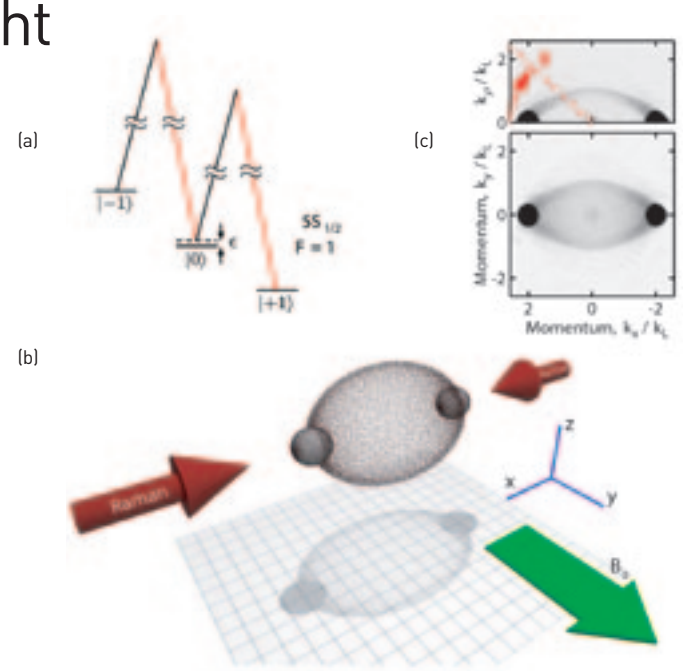
Controlling Atomic Interactions with Light

For most of the 20th century, atomic physicists used light to probe atoms. Today, scientists use light to manipulate particles with unprecedented control, routinely cooling atoms to a few billionths of a degree above absolute zero. This ability is vital for developing atomic clocks, quantum computing and the use of ultracold quantum gases to study many-body physics. Now, we report that we can use light to modify the interactions between atoms in a new way.[1]

At ultracold temperatures, the interactions between alkali atoms are usually relatively simple. The de Broglie wavelength associated with an ultracold atom is large (>100 nm for T 100 nK) compared to the characteristic range of the interatomic Van der Waals potential (5 nm). As such, two colliding atoms do not resolve any structure about each other and scatter isotropically (s-wave scattering). While the strength of atomic interactions can be changed using a Feshbach resonance,[2] the character of the interaction has been restricted to purely s-wave scattering—until now.

The experimental demonstration of light-modified interactions required dressing a ^{87}Rb Bose-Einstein condensate (BEC) with counter-propagating laser beams designed to couple the hyperfine spin states of an atom. This light enables the linking of the internal states of an atom to its external motion—the key physical mechanism behind altered atomic interactions.[3] When two dressed atoms collide, the change in their momenta now also requires a modification in their spin composition. In certain scattering directions, the overlap between the initial and final spin states is less favorable than others, resulting in a new anisotropic scattering probability.

We observed this anisotropic scattering by colliding two BECs with equal and opposite momenta in the presence of the dressing lasers.



(a) Two counter-propagating Raman laser beams couple the hyperfine spin states in ^{87}Rb's electronic ground state. (b) Schematic of two Raman-dressed Bose-Einstein condensates after a collision, indicating the atomic distribution as imaged after time-of-flight expansion. (c) Image of a scattering halo (bottom pane) and its inverse Abel transform (upper pane), showing the anisotropic distribution of scattered atoms.

We imaged the distribution of scattered atoms after the condensates had separated, revealing the predicted anisotropy. This modified scattering can be interpreted as the light effectively screening the native atomic interaction, reminiscent of effects familiar in condensed matter systems, such as the screening of the Coulomb interaction between a pair of electrons by the collective response of the remaining electrons.

Being able to control atomic interactions with light gives experimentalists a new tool with which to access exotic quantum states of matter in an ultracold atom context. For example, extending the technique demonstrated here with bosons to ultracold fermions is predicted to allow for the creation of a p-wave superfluid.[4] Such a state should support Majorana fermions, enigmatic particles that are their own antiparticle. OPN

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