New Journal of Physics
The open-access journal for physics

Observation of a kilogram-scale oscillator near its quantum ground state

B Abbott[1], R Abbott[1], R Adhikari[1], P Ajith[2], B Allen[2,3], G Allen[4], R Amin[5], S B Anderson[1], W G Anderson[3], M A Arain[6], M Araya[1], H Armandula[1], P Armor[3], Y Aso[7], S Aston[8], P Aufmuth[9], C Aulbert[2], S Babak[10], S Ballmer[1], H Bantilan[11], B C Barish[1], C Barker[12], D Barker[12], B Barr[13], P Barriga[14], M A Barton[13], M Bastarrika[13], K Bayer[15], J Betzwieser[1], P T Beyersdorf[16], I A Bilenko[17], G Billingsley[1], R Biswas[3], E Black[1], K Blackburn[1], L Blackburn[15], D Blair[14], B Bland[12], T P Bodiya[15], L Bogue[18], R Bork[1], V Boschi[1], S Bose[19], P R Brady[3], V B Braginsky[17], J E Brau[20], M Brinkmann[2], A Brooks[1], D A Brown[21], G Brunet[15], A Bullington[4], A Buonanno[22], O Burmeister[2], R L Byer[4], L Cadonati[23], G Cagnoli[13], J B Camp[24], J Cannizzo[24], K Cannon[1], J Cao[15], L Cardenas[1], T Casebolt[4], G Castaldi[25], C Cepeda[1], E Chalkley[13], P Charlton[26], S Chatterji[1], S Chelkowski[8], Y Chen[10,27], N Christensen[11], D Clark[4], J Clark[13], T Cokelaer[28], R Conte[29], D Cook[12], T Corbitt[15,56], D Coyne[1], J D E Creighton[3], A Cumming[13], L Cunningham[13], R M Cutler[8], J Dalrymple[21], S Danilishin[17], K Danzmann[2,9], G Davies[28], D DeBra[4], J Degallaix[10], M Degree[4], V Dergachev[30], S Desai[31], R DeSalvo[1], S Dhurandhar[32], M Díaz[33], J Dickson[34], A Dietz[28], F Donovan[15], K L Dooley[6], E E Doomes[35], R W P Drever[36], I Duke[15], J-C Dumas[14], R J Dupuis[1], J G Dwyer[7], C Echols[1], A Effler[12], P Ehrens[1], E Espinoza[1], T Etzel[1], T Evans[18], S Fairhurst[28], Y Fan[14], D Fazi[1], H Fehrmann[2], M M Fejer[4], L S Finn[31], K Flasch[3], N Fotopoulos[3], A Freise[8], R Frey[20], T Fricke[1,37], P Fritschel[15], V V Frolov[18], M Fyffe[18], J Garofoli[12], I Gholami[10], J A Giaime[5,18], S Giampanis[37], K D Giardina[18], K Goda[15], E Goetz[30], L Goggin[1], G González[5], S Gossler[2], R Gouaty[5], A Grant[13], S Gras[14], C Gray[12], M Gray[34], R J S Greenhalgh[38], A M Gretarsson[39], F Grimaldi[15], R Grosso[33], H Grote[2], S Grunewald[10], M Guenther[12], E K Gustafson[1], R Gustafson[30], B Hage[9], J M Hallam[8], D Hammer[3], C Hanna[5], J Hanson[18], J Harms[2], G Harry[15], E Harstad[20], K Hayama[33],

1367-2630/09/073032+13$30.00

T Hayler[38], J Heefner[1], I S Heng[13], M Hennessy[4], A Heptonstall[13], M Hewitson[2], S Hild[8], E Hirose[21], D Hoak[18], D Hosken[40], J Hough[13], S H Huttner[13], D Ingram[12], M Ito[20], A Ivanov[1], B Johnson[12], W W Johnson[5], D I Jones[41], G Jones[28], R Jones[13], L Ju[14], P Kalmus[7], V Kalogera[42], S Kamat[7], J Kanner[22], D Kasprzyk[8], E Katsavounidis[15], K Kawabe[12], S Kawamura[43], F Kawazoe[43], W Kells[1], D G Keppel[1], F Ya Khalili[17], R Khan[7], E Khazanov[44], C Kim[42], P King[1], J S Kissel[5], S Klimenko[6], K Kokeyama[43], V Kondrashov[1], R K Kopparapu[31], D Kozak[1], I Kozhevatov[44], B Krishnan[10], P Kwee[9], P K Lam[34], M Landry[12], M M Lang[31], B Lantz[4], A Lazzarini[1], M Lei[1], N Leindecker[4], V Leonhardt[43], I Leonor[20], K Libbrecht[1], H Lin[6], P Lindquist[1], N A Lockerbie[45], D Lodhia[8], M Lormand[18], P Lu[4], M Lubinski[12], A Lucianetti[6], H Lück[2,9], B Machenschalk[2], M MacInnis[15], M Mageswaran[1], K Mailand[1], V Mandic[46], S Márka[7], Z Márka[7], A Markosyan[4], J Markowitz[15], E Maros[1], I Martin[13], R M Martin[6], J N Marx[1], K Mason[15], F Matichard[5], L Matone[7], R Matzner[47], N Mavalvala[15], R McCarthy[12], D E McClelland[34], S C McGuire[35], M McHugh[48], G McIntyre[1], G McIvor[47], D McKechan[28], K McKenzie[34], T Meier[9], A Melissinos[37], G Mendell[12], R A Mercer[6], S Meshkov[1], C J Messenger[2], D Meyers[1], H Miao[14], J Miller[1,13], J Minelli[31], S Mitra[32], V P Mitrofanov[17], G Mitselmakher[6], R Mittleman[15], O Miyakawa[1], B Moe[3], S Mohanty[33], G Moreno[12], K Mossavi[2], C Mow-Lowry[34], G Mueller[6], S Mukherjee[33], H Mukhopadhyay[32], H Müller-Ebhardt[2], J Munch[40], P Murray[13], E Myers[12], J Myers[12], T Nash[1], J Nelson[13], G Newton[13], A Nishizawa[43], K Numata[24], J O'Dell[38], G Ogin[1], B O'Reilly[18], R O'Shaughnessy[31], D J Ottaway[15], R S Ottens[6], H Overmier[18], B J Owen[31], Y Pan[22], C Pankow[6], M A Papa[3,10], V Parameshwaraiah[12], P Patel[1], M Pedraza[1], S Penn[49], A Perreca[8], T Petrie[31], I M Pinto[25], M Pitkin[13], H J Pletsch[2], M V Plissi[13], F Postiglione[29], M Principe[25], R Prix[2], V Quetschke[6], F Raab[12], D S Rabeling[34], H Radkins[12], N Rainer[2], M Rakhmanov[50], M Ramsunder[31], H Rehbein[2], S Reid[13], D H Reitze[6], R Riesen[18], K Riles[30], B Rivera[12], N A Robertson[1,13], C Robinson[28], E L Robinson[8], S Roddy[18], A Rodriguez[5], A M Rogan[19], J Rollins[7], J D Romano[33], J Romie[18], R Route[4], S Rowan[13], A Rüdiger[2], L Ruet[15], P Russell[1], K Ryan[12], S Sakata[43], M Samidi[1], L Sancho de la Jordana[51], V Sandberg[12],

V Sannibale[1], S Saraf[52], P Sarin[15], B S Sathyaprakash[28], S Sato[43], P R Saulson[21], R Savage[12], P Savov[27], S W Schediwy[14], R Schilling[2], R Schnabel[2], R Schofield[20], B F Schutz[10,28], P Schwinberg[12], S M Scott[34], A C Searle[34], B Sears[1], F Seifert[2], D Sellers[18], A S Sengupta[1], P Shawhan[22], D H Shoemaker[15], A Sibley[18], X Siemens[3], D Sigg[12], S Sinha[4], A M Sintes[10,51], B J J Slagmolen[34], J Slutsky[5], J R Smith[21], M R Smith[1], N D Smith[15], K Somiya[2,10], B Sorazu[13], L C Stein[15], A Stochino[1], R Stone[33], K A Strain[13], D M Strom[20], A Stuver[18], T Z Summerscales[53], K-X Sun[4], M Sung[5], P J Sutton[28], H Takahashi[10], D B Tanner[6], R Taylor[1], R Taylor[13], J Thacker[18], K A Thorne[31], K S Thorne[27], A Thüring[9], K V Tokmakov[13], C Torres[18], C Torrie[13], G Traylor[18], M Trias[51], W Tyler[1], D Ugolini[54], J Ulmen[4], K Urbanek[4], H Vahlbruch[9], C Van Den Broeck[28], M van der Sluys[42], S Vass[1], R Vaulin[3], A Vecchio[8], J Veitch[8], P Veitch[40], A Villar[1], C Vorvick[12], S P Vyatchanin[17], S J Waldman[1], L Wallace[1], H Ward[13], R Ward[1], M Weinert[2], A Weinstein[1], R Weiss[15], S Wen[5], K Wette[34], J T Whelan[10], S E Whitcomb[1], B F Whiting[6], C Wilkinson[12], P A Willems[1], H R Williams[31], L Williams[6], B Willke[2,9], I Wilmut[38], W Winkler[2], C C Wipf[15], A G Wiseman[3], G Woan[13], R Wooley[18], J Worden[12], W Wu[6], I Yakushin[18], H Yamamoto[1], Z Yan[14], S Yoshida[50], M Zanolin[39], J Zhang[30], L Zhang[1], C Zhao[14], N Zotov[55], M Zucker[15] and J Zweizig[1] (LIGO Scientific Collaboration)

[1] LIGO—California Institute of Technology, Pasadena, CA 91125, USA
[2] Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany
[3] University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA
[4] Stanford University, Stanford, CA 94305, USA
[5] Louisiana State University, Baton Rouge, LA 70803, USA
[6] University of Florida, Gainesville, FL 32611, USA
[7] Columbia University, New York, NY 10027, USA
[8] University of Birmingham, Birmingham B15 2TT, UK
[9] Leibniz Universität Hannover, D-30167 Hannover, Germany
[10] Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-14476 Golm, Germany
[11] Carleton College, Northfield, MN 55057, USA
[12] LIGO Hanford Observatory, Richland, WA 99352, USA
[13] University of Glasgow, Glasgow G12 8QQ, UK
[14] University of Western Australia, Crawley, WA 6009, Australia
[15] LIGO—Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[16] San Jose State University, San Jose, CA 95192, USA
[17] Moscow State University, Moscow, 119992, Russia

[18] LIGO Livingston Observatory, Livingston, LA 70754, USA
[19] Washington State University, Pullman, WA 99164, USA
[20] University of Oregon, Eugene, OR 97403, USA
[21] Syracuse University, Syracuse, NY 13244, USA
[22] University of Maryland, College Park, MD 20742 USA
[23] University of Massachusetts, Amherst, MA 01003 USA
[24] NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
[25] University of Sannio at Benevento, I-82100 Benevento, Italy
[26] Charles Sturt University, Wagga Wagga, NSW 2678, Australia
[27] Caltech-CaRT, Pasadena, CA 91125, USA
[28] Cardiff University, Cardiff, CF24 3AA, UK
[29] University of Salerno, 84084 Fisciano (Salerno), Italy
[30] University of Michigan, Ann Arbor, MI 48109, USA
[31] The Pennsylvania State University, University Park, PA 16802, USA
[32] Inter-University Centre for Astronomy and Astrophysics, Pune-411007, India
[33] The University of Texas at Brownsville and Texas Southmost College, Brownsville, TX 78520, USA
[34] Australian National University, Canberra, 0200, Australia
[35] Southern University and A& M College, Baton Rouge, LA 70813, USA
[36] California Institute of Technology, Pasadena, CA 91125, USA
[37] University of Rochester, Rochester, NY 14627, USA
[38] Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK
[39] Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA
[40] University of Adelaide, Adelaide, SA 5005, Australia
[41] University of Southampton, Southampton SO17 1BJ, UK
[42] Northwestern University, Evanston, IL 60208, USA
[43] National Astronomical Observatory of Japan, Tokyo 181-8588, Japan
[44] Institute of Applied Physics, Nizhny Novgorod, 603950, Russia
[45] University of Strathclyde, Glasgow G1 1XQ, UK
[46] University of Minnesota, Minneapolis, MN 55455, USA
[47] The University of Texas at Austin, Austin, TX 78712, USA
[48] Loyola University, New Orleans, LA 70118, USA
[49] Hobart and William Smith Colleges, Geneva, NY 14456, USA
[50] Southeastern Louisiana University, Hammond, LA 70402, USA
[51] Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain
[52] Sonoma State University, Rohnert Park, CA 94928, USA
[53] Andrews University, Berrien Springs, MI 49104 USA
[54] Trinity University, San Antonio, TX 78212, USA
[55] Louisiana Tech University, Ruston, LA 71272, USA
E-mail: tcorbitt@ligo.mit.edu

New Journal of Physics **11** (2009) 073032 (13pp)
Received 20 February 2009
Published 16 July 2009
Online at http://www.njp.org/
doi:10.1088/1367-2630/11/7/073032

[56] Author to whom any correspondence should be addressed.

Abstract. We introduce a novel cooling technique capable of approaching the quantum ground state of a kilogram-scale system—an interferometric gravitational wave detector. The detectors of the Laser Interferometer Gravitational-wave Observatory (LIGO) operate within a factor of 10 of the standard quantum limit (SQL), providing a displacement sensitivity of 10^{-18} m in a 100 Hz band centered on 150 Hz. With a new feedback strategy, we dynamically shift the resonant frequency of a 2.7 kg pendulum mode to lie within this optimal band, where its effective temperature falls as low as 1.4 μK, and its occupation number reaches about 200 quanta. This work shows how the exquisite sensitivity necessary to detect gravitational waves can be made available to probe the validity of quantum mechanics on an enormous mass scale.

Contents

Observation of quantum effects such as ground state cooling [1]–[15], quantum jumps [16], optical squeezing [17], mechanical squeezing [18]–[20] and entanglement [21]–[26] that involve macroscopic mechanical systems are the subject of intense experimental effort [27]. The first step toward engineering a non-classical state of a mechanical oscillator is to cool it, minimizing the thermal occupation number of the mode. Any mechanical coupling to the environment admits thermal noise that randomly drives the system's motion, as dictated by the fluctuation–dissipation theorem [28], but 'cold' frictionless forces, such as optical or electronic feedback, can suppress this motion, hence cooling the oscillator.

Two types of forces have recently proven valuable for cooling. The first is a frictionless damping force, originating either from an electronic servo system ('cold damping') [4, 29, 30] or from photothermal or radiation pressure forces in a detuned cavity ('cavity cooling') [1]–[3], [5, 6, 8]; this force reduces the motion of the oscillator while also diminishing its quality factor. The second is an optical restoring force, which increases the resonant frequency of the oscillator without additional friction, effectively increasing its quality factor [7, 10]. To reach the quantum regime in experiments exploiting these techniques, a low noise oscillator's position must be monitored by a highly sensitive readout device. By providing both of these features, the Laser Interferometer Gravitational-wave Observatory (LIGO) interferometers present a unique opportunity to cool kilogram-scale mirrors to enticingly low temperatures. Although the LIGO interferometers do not have sufficiently large optical restoring forces for the second effect to be significant, their active control systems may instead be used to reproduce the effect.

1. The LIGO interferometers

LIGO operates three kilometer-scale interferometric detectors with the goal of directly detecting gravitational waves of astrophysical origin [31, 32]. The measurements reported here were performed at LIGO's Hanford Observatory. The detector shown in figure 1 comprises a Michelson interferometer with a 4 km long Fabry–Perot cavity of finesse 220 placed in each arm to increase the sensitivity of the detector. Each mirror of the interferometer has mass $M = 10.8$ kg, and is suspended from a vibration-isolated platform on a fine wire to form a pendulum with frequency $\Omega_p = 0.74$ Hz, to shield it from external forces and to enable it to respond to a gravitational wave as a mechanically free mass above the natural resonant frequency. To minimize the effects of laser shot noise, the interferometer operates with high power levels; approximately 400 W of laser power of wavelength 1064 nm is incident on the beam splitter, resulting in over 15 kW of laser power circulating in each arm cavity. The present detectors are sensitive to changes in relative mirror displacements of about 10^{-18} m in a 100 Hz band centered around 150 Hz (figure 2). This low noise level allows for the preparation of low-energy states for the oscillator mode considered next.

The four mirrors of the LIGO interferometer (figure 1) are each an extended object with a displacement x_i ($i = 1, \ldots, 4$) defined along the optical beam axis. The servo control system that keeps the interferometer mirrors at the resonant operating point is an essential component of this study. While all longitudinal and angular degrees of freedom of the mirrors are actively controlled, our discussion is limited to the differential arm cavity motion, which is the degree of freedom excited by a passing gravitational wave, and hence also the most sensitive to mirror displacements. This mode corresponds to the differential motion of the centers of mass of the four mirrors, $x_c = (x_1 - x_2) - (x_3 - x_4)$, and has a reduced mass of $M_r = 2.7$ kg. A signal proportional to differential length changes is measured at the antisymmetric output of the beam splitter, as shown in figure 1. This signal is filtered by a servo compensation network before being applied as a force on the differential degree of freedom by voice coils that actuate magnets affixed to the mirrors.

2. The cooling mechanism

The degree of freedom that is of interest as a quantum particle is the differential mirror motion x_c. However, optical measurements probe the location of the mirror surface (averaged over the optical beam), which differs from center-of-mass location due to the mirror's *internal* thermal noise, and include a *sensing* noise due to the laser shot noise. Combining these noises into a total displacement noise X_N, the output signal is written as

$$x_s = x_c + X_N. \tag{1}$$

The center-of-mass motion is also subject to a noise force F_N (including, for example, the thermally driven motion of the mirror suspensions and the seismic motion of the ground that couples through the suspensions) and a feedback force that is proportional to x_s. The resulting equation of motion in the frequency domain is given by:

$$-M_r \left[\Omega^2 - \mathrm{i}\,\Omega\,\Omega_p\,\phi(\Omega) - \Omega_p^2\right] x_c = F_N - K(\Omega) x_s. \tag{2}$$

Here $K(\Omega)$ is the frequency-domain feedback filter kernel, and the $\phi(\Omega)$ term accounts for mechanical damping. For a viscously damped pendulum with quality factor $Q_p = \Omega_p / \Gamma_p$

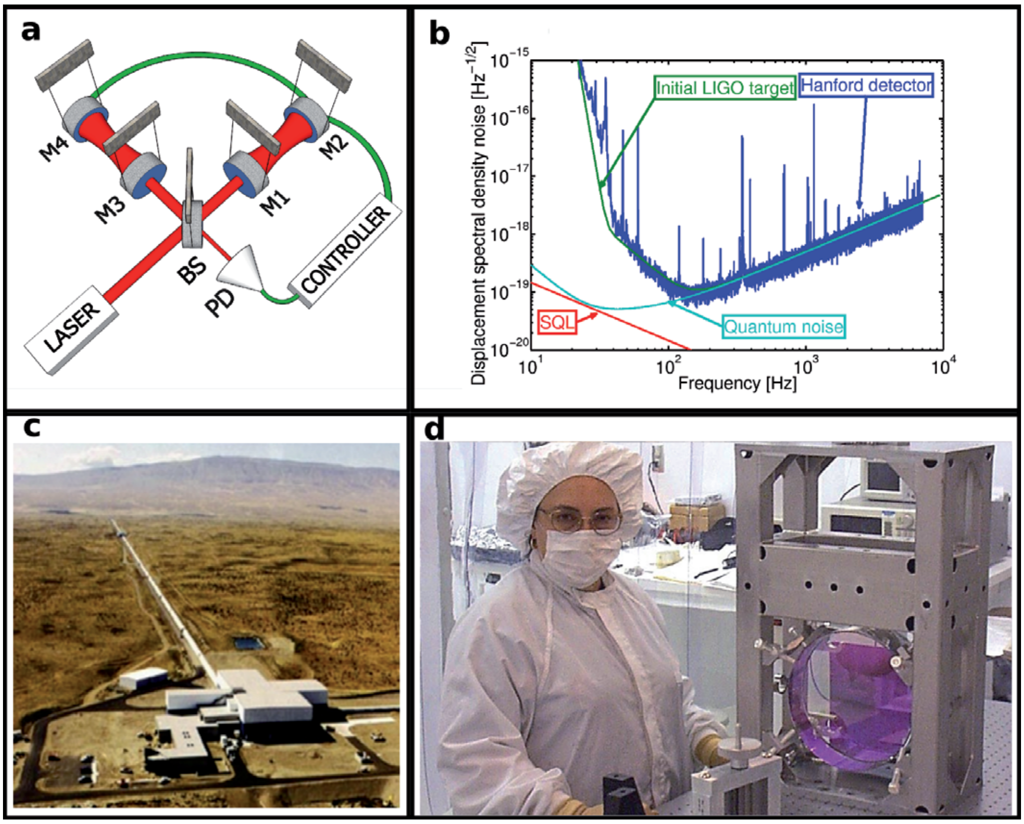

Figure 1. (a) Optical layout of a LIGO interferometer. Light reflected from the two Fabry–Perot cavities formed by input and end mirrors, M_1–M_4, is recombined at the beam splitter (BS). To control the differential degree of freedom, an optical signal proportional to mirror displacement is measured on the photodetector (PD), and fed back as a differential force on the mirrors, after appropriate filtering to form restoring and damping forces. (b) The spectral displacement noise density of the differential mode of motion of the LIGO 4 km interferometer at the Hanford Observatory is shown. Also shown is the target sensitivity and the quantum noise contribution, which consists of shot noise above 30 Hz and radiation pressure noise below. The standard quantum limit (SQL) is also shown, and the closest approach to the measured sensitivity is about a factor of 10 near 150 Hz. (c) An aerial photograph of the LIGO Hanford site in the state of Washington is shown. (d) A photograph of a 10.8 kg mirror is shown. Photographs courtesy of the MIT/Caltech LIGO Laboratory.

(Ω_p and Γ_p correspond to the real part and twice the imaginary part of the complex eigenfrequency of the pendulum), $\phi(\Omega) = 1/Q_p$. If the damping is not viscous, but instead caused by internal friction, $\phi(\Omega)$ takes on a more complex form [28]. Combining equations (1) and (2), the equation of motion for the center-of-mass is obtained:

$$-M_r\left[\Omega^2 - i\,\Omega\,\Omega_p\,\phi(\Omega) - \Omega_p^2 - K(\Omega)/M_r\right]x_c = F_N - K(\Omega)X_N. \tag{3}$$

In this experiment, the control kernel is adjusted so that

$$K(\Omega)/M_r \approx \Omega_{\rm eff}^2 + i\Omega\Gamma_{\rm eff} \tag{4}$$

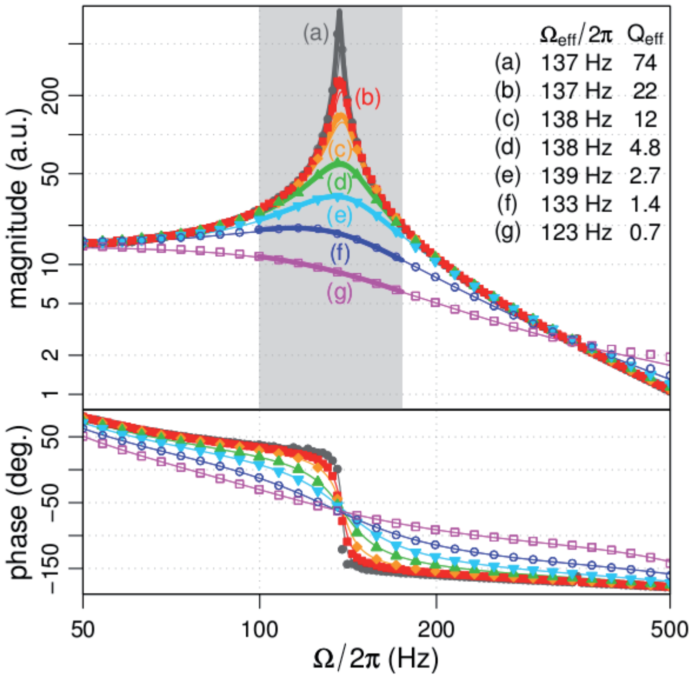

Figure 2. Response function of mirror displacement to an applied force, for various levels of damping. The points are measured data, the thin lines are a zero fit parameter model of the complete feedback loop, and the thick lines spanning the resonance (shown in the shaded region) are fitted Lorentzians, from which the effective resonant frequency and quality factor are derived for each configuration.

with $\Omega_{\rm eff}$ and $\Gamma_{\rm eff}$ much larger than $\Omega_{\rm p}$ and $\Gamma_{\rm p}$, respectively, such that the modified dynamics of $x_{\rm c}$ are given by a damped oscillator driven by random forces:

$$-M_{\rm r}[\Omega^2 - {\rm i}\Omega\Gamma_{\rm eff} - \Omega^2_{\rm eff}]\, x_{\rm c} = F_{\rm N} - K(\Omega)X_{\rm N}. \tag{5}$$

An electro-optical potential well in which the mirrors oscillate is thus created.

The output of our experiment measures $x_{\rm s}$, and in order to deduce true mirror motion $x_{\rm c}$, the limiting sources of noise must be considered. If noise predominantly drives the center-of-mass motion, i.e. $F_{\rm N} \gg K(\Omega)X_{\rm N}$, then $x_{\rm s} \approx x_{\rm c}$ (see equation (1)) and the measured signal corresponds to the center-of-mass motion. However, in the case that surface or sensing noise dominates, i.e. $K(\Omega)X_{\rm N} \gg F_{\rm N}$, then a correction factor must be applied to the measured signal to deduce the center-of-mass motion. Taking equations (1) and (5), in the limit that $F_{\rm N} = 0$, we obtain

$$x_{\rm c} = \frac{K(\Omega)}{M_{\rm r}\Omega^2} x_{\rm s}. \tag{6}$$

If the levels of each noise $X_{\rm N}$ and $F_{\rm N}$ are not precisely known, then one can make a conservative correction by applying a factor $\max(1, |K(\Omega)/M_{\rm r}\Omega^2|)$ to determine the worst possible center-of mass motion, thereby accounting for the fact that the servo can inject noise back onto the oscillator. The effective temperature of the mode may then be obtained:

$$T_{\rm eff} = \frac{M_{\rm r}\Omega^2_{\rm eff}\delta x^2_{\rm rms}}{k_{\rm B}}, \tag{7}$$

where

$$\delta x_{\rm rms}^2 = \int_0^\infty \max\left(1, \frac{K(\Omega)}{M_{\rm r}\Omega^2}\right)^2 S_{x_{\rm s}}(\Omega){\rm d}\Omega \equiv \int_0^\infty S_{x_{\rm d}}{\rm d}\Omega. \tag{8}$$

$S_{x_{\rm s}}$ is the single-sided power spectral density of the measured motion $x_{\rm s}$ and $S_{x_{\rm d}}$ includes the correction factor. At large feedback gains, the measured noise $S_{x_{\rm s}}$ may be arbitrarily suppressed, however, the mirror motion will reach a finite level as limited by the detection noise $X_{\rm N}$. This 'squashing' effect has been explored previously [9, 33], and the calculation of $S_{x_{\rm d}}$ avoids underestimates of the mirror motion. It is impossible to reliably measure the mirror motion at arbitrarily high frequencies, and the integral in equation (8) will diverge in any real system. The integration must therefore be limited in its frequency band, as is later discussed. Finally, the corresponding occupation number may be determined by

$$N_{\rm eff} = \frac{k_{\rm B}T_{\rm eff}}{\hbar\Omega_{\rm eff}}. \tag{9}$$

$K(\Omega)$ of equation (4) is formed by convolving the position-dependent output signal with filter functions corresponding to the real and imaginary parts of the feedback kernel $K(\Omega)$. In the LIGO feedback system, there are additional filters and propagation delays that cause deviations from the ideal cold, damped spring, at high and low frequencies. Below 100 Hz, $K(\Omega)$ increases sharply to suppress seismically driven motion; at high frequencies (above a few kilohertz), $K(\Omega)$ decreases precipitously to prevent the control system from feeding shot noise back onto the mirrors. However, in the frequency band important for this measurement (near the electro-optical resonance), the feedback is well approximated by a spring and damping force, as shown in figure 2.

3. Measurement results and discussion

The servo control loops of the LIGO interferometers are optimized to minimize noise coupling to measurement of the differential mode motion of the mirrors. The modifications to the servo loops to create a nearly ideal cold spring at $\Omega_{\rm eff} = 140$ Hz do not significantly affect the noise limits, shown in figure 1. Figure 3 shows the amplitude spectral density of mirror displacement for varying levels of cold damping. To infer the effective temperature of the mode, its effective frequency $\Omega_{\rm eff}$ and an estimation of the root-mean-square displacement fluctuation $\delta x_{\rm rms}$ must be determined. First the differential mirror motion is driven and the response is measured, as shown in figure 2. These response functions are fit to a damped oscillator model; $\Omega_{\rm eff}$ and $Q_{\rm eff}$ are products of the fit. Then $\delta x_{\rm rms}$ is computed by integrating the spectrum in the band from 100 to 170 Hz, as described in equation (8). The sensitivity in this frequency band is limited by laser shot noise that enters into $X_{\rm N}$. To correct for the finite integration band, the result is scaled by setting our measured spectrum equal to the integral over the same frequency band of a thermally driven oscillator spectrum,

$$S_{x_{\rm th}}(\Omega) = \frac{4k_{\rm B}T_{\rm eff}\Gamma_{\rm eff}/M_{\rm r}}{(\Omega_{\rm eff}^2 - \Omega^2)^2 + \Omega^2\Gamma_{\rm eff}^2}. \tag{10}$$

In this way, a minimum effective temperature $T_{\rm eff} = 1.4 \pm 0.2\,\mu$K is measured, corresponding to thermal occupation number $N_{\rm eff} = 234 \pm 35$. Systematic error of 15% in the calibration

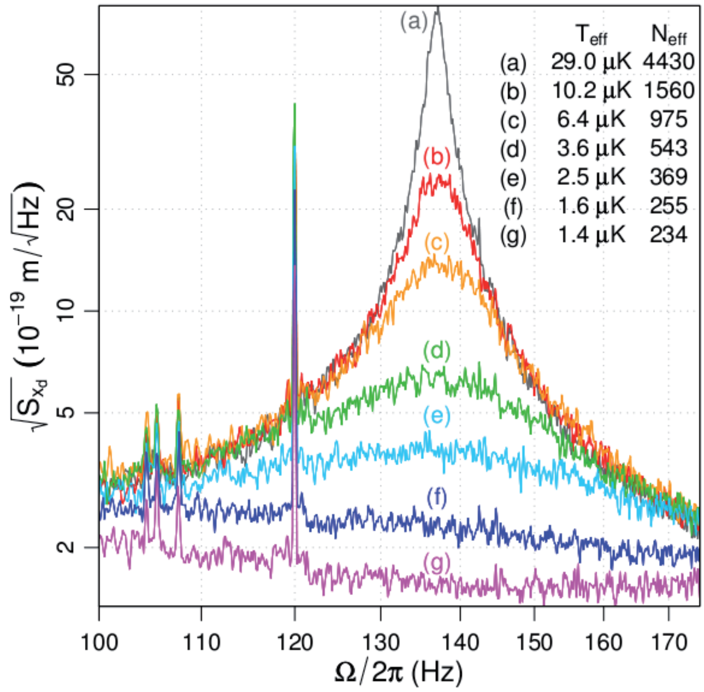

Figure 3. Amplitude spectral density of displacement in the frequency band of integration. The curves (from highest to lowest) were produced by applying increasingly strong cold damping to the oscillator, corresponding to the measurements of figure 2. The depression in the lowest curve is due to the shape of the background noise spectrum; the effects of the servo are corrected for according to equations (1)–(8). The narrow line features between 100 and 110 Hz are mechanical resonances of auxiliary subsystems, and a 120 Hz power line harmonic is also visible. The predominant noise is laser shot noise.

dominates statistical error in these uncertainty estimates. The limits to integration were chosen as a compromise between having a wide limit, and choosing frequencies at which mirror motion is sensed. In the limit that the width of the integration band approaches 0, the lowest temperature achieved approaches 0.9 μK. For larger integration limits, the temperature diverges because of the increased uncertainty at high frequency caused by shot noise (as occurs in all experiments). The spectra in figure 3 are predominantly limited by shot noise in the measurement band. It may at first appear unusual to associate a temperature with a device limited by shot noise, rather than thermal noise. However, the above calculations are justified, since the ultimate limit to experiments such as this is known to arise from optical noise [34].

4. Cooling to the quantum limit

An interesting question arises as to whether this technique can lead to ground state cooling of the electromechanical oscillator. To mitigate the shot noise limit, which arises due to the fluctuating number of photons detected, the laser power could be increased. However, radiation pressure noise (a fluctuating force exerted on the mirrors due to the shot noise of the laser) increases with laser power and will ultimately limit the sensitivity. The SQL is obtained when shot noise and radiation pressure noise contribute equally to the total quantum noise [35]. Hence, the continuous displacement measurement required for servo feedback does introduce an additional term to the uncertainty relation for the oscillator position and momentum fluctuations due to measurement-induced steady state decoherence. If, however, the classical noises (such as thermal) are reduced significantly below the SQL, active feedback, with the appropriate control kernel, is capable of cooling the electro-optic oscillator to its motional ground state [36].

5. Future prospects with LIGO

In the coming years, two upgrades of the LIGO detectors are planned. The first, Enhanced LIGO, is presently underway with an expected completion date in 2009, and seeks to improve the sensitivity of the instruments above 40 Hz. The improvement in displacement sensitivity in the frequency band around 150 Hz, where the cold spring measurements were performed, is expected to be about a factor of 2. Subsequently, a major upgrade, Advanced LIGO, expected to be completed in 2014, should give a factor of 10–15 improvement in displacement sensitivity relative to that of the detector used for this work (with a concomitant factor of 4 increase in mass). In Advanced LIGO, the laser power circulating in the Fabry–Perot cavities should exceed 800 kW, permitting strong restoring forces to be generated optically. Enhanced LIGO is expected to reach $\sim$6 times lower occupation number, approaching 40 quanta, and with Advanced LIGO, the detectors will be operating at the SQL, allowing the ground state to be approached.

As they approach the SQL, these devices should enable novel experimental demonstrations of quantum theory that involve kilogram-scale test masses [25, 37, 38]. The present work, reaching microkelvin temperatures, provides evidence that interferometric gravitational wave detectors, designed as sensitive probes of general relativity and astrophysical phenomena, can also become sensitive probes of macroscopic quantum mechanics.

Acknowledgments

We gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory and the Science and Technology Facilities Council of the United Kingdom, the Max-Planck-Society, and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector. We also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the Council of Scientific and Industrial Research of India, the Istituto Nazionale di Fisica Nucleare of Italy, the Spanish Ministerio de Educacion y Ciencia, the Conselleria d'Economia Hisenda i Innovacio of the Govern de les Illes Balears, the Scottish Funding Council, the Scottish Universities Physics Alliance, The National Aeronautics and Space Administration, the Carnegie Trust, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation and the Alfred P Sloan Foundation.

References

[1] Metzger C H and Karrai K 2004 Cavity cooling of a microlever *Nature* **432** 1002

[2] Gigan S, Böhm H, Paternostro M, Blaser F, Langer G, Hertzberg J, Schwab K, Bäuerle D, Aspelmeyer M and Zeilinger A 2006 Self-cooling of a micromirror by radiation pressure *Nature* **444** 67

[3] Arcizet O, Cohadon P-F, Briant T, Pinard M and Heidmann A 2006 Radiation pressure cooling and optomechanical instability of a micromirror *Nature* **444** 71

[4] Kleckner D and Bouwmeester D 2006 Sub-kelvin optical cooling of a micromechanical resonator *Nature* **444** 75

[5] Naik A, Buu O, LaHaye M D, Armour A D, Clerk A A, Blencowe M P and Schwab K C 2006 Cooling a nanomechanical resonator with quantum back-action *Nature* **443** 193

[6] Schliesser A, Del'Haye P, Nooshi N, Vahala K J and Kippenberg T J 2006 Radiation pressure cooling of a micromechanical oscillator using dynamical backaction *Phys. Rev. Lett.* **97** 243905

[7] Corbitt T, Chen Y, Innerhofer E, Müller-Ebhardt H, Ottaway D, Rehbein H, Sigg D, Whitcomb S, Wipf C and Mavalvala N 2007 An all-optical trap for a gram-scale mirror *Phys. Rev. Lett.* **98** 150802

[8] Harris J G E, Zwickl B M and Jayich A M 2007 Stable, mode-matched, medium-finesse optical cavity incorporating amicrocantilever mirror *Rev. Sci. Instrum.* **78** 013107

[9] Poggio M, Degen C L, Mamin H J and Rugar D 2007 Feedback cooling of a cantilever's fundamental mode below 5 mK *Phys. Rev. Lett.* **99** 017201

[10] Corbitt T, Wipf C, Bodiya T, Ottaway D, Sigg D, Smith N, Whitcomb S and Mavalvala N 2007 Optical dilution and feedback cooling of a gram-scale oscillator to 6.9 mK *Phys. Rev. Lett.* **99** 160801

[11] Mow-Lowry C M, Mullavey A J, Goßler S, Gray M B and McClelland D E 2008 Cooling of a gram-scale cantilever flexure to 70 mK with a servo-modified optical spring *Phys. Rev. Lett.* **100** 010801

[12] Vinante A *et al* 2008 Feedback cooling of the normal modes of a massive electromechanical system to submillikelvin temperature *Phys. Rev. Lett.* **101** 033601

[13] Regal C A, Teufel J D and Lehnert K W 2008 Measuring nanomechanical motion with a microwave cavity interferometer *Nat. Phys.* **4** 555

[14] Schliesser A, Arcizet O, Rivire R and Kippenberg T J 2009 Resolved-sideband cooling and measurement of a micromechanical oscillator close to the quantum limit arXiv:0901.1456

[15] Groeblacher S, Hertzberg J B, Vanner M R, Gigan S, Schwab K and Aspelmeyer M 2009 Demonstration of an ultracold micro-optomechanical oscillator in a cryogenic cavity arXiv:0901.1801

[16] Thompson J D, Zwickl B M, Jayich A M, Marquardt F, Girvin S M and Harris J G E 2008 Strong dispersive coupling of a high-finesse cavity to a micromechanical membrane *Nature* **452** 72

[17] Corbitt T, Chen Y, Khalili F, Ottaway D, Vyatchanin S, Whitcomb S and Mavalvala N 2006 Squeezed-state source using radiation-pressure-induced rigidity *Phys. Rev.* A **73** 023801

[18] Rabl P, Shnirman A and Zoller P 2004 Generation of squeezed states of nanomechanical resonators by reservoir engineering *Phys. Rev.* B **70** 205304

[29] Ruskov R, Schwab K and Korotkov A N 2005 Squeezing of a nanomechanical resonator by quantum nondemolition measurement and feedback *Phys. Rev.* B **71** 235407

[20] Clerk A A, Marquardt F and Jacobs K 2008 Back-action evasion and squeezing of a mechanical resonator using a cavity detector *New J. Phys.* **10** 095010

[21] Bose S, Jacobs K and Knight P L 1997 Preparation of nonclassical states in cavities with a moving mirror *Phys. Rev.* A **56** 4175

[22] Armour A D, Blencowe M P and Schwab K C 2002 Entanglement and decoherence of a micromechanical resonator via coupling to a Cooper-pair box *Phys. Rev. Lett.* **88** 148301

[23] Marshall W, Simon C, Penrose R and Bouwmeester D 2003 Towards quantum superpositions of a mirror 2003 *Phys. Rev. Lett.* **91** 130401

[24] Vitali D, Gigan S, Ferreira A, Böhm H R, Tombesi P, Guerreiro A, Vedral V, Zeilinger A and Aspelmeyer M 2007 Optomechanical entanglement between a movable mirror and a cavity field *Phys. Rev. Lett.* **98** 030405

[25] Müller-Ebhardt H, Rehbein H, Schnabel R, Danzmann K and Chen Y 2007 Entanglement of macroscopic test masses and the standard quantum limit in laser interferometry *Phys. Rev. Lett.* **100** 013601

[26] Wipf C, Corbitt T, Chen Y and Mavalvala N 2008 Route to observing ponderomotive entanglement with an optically trapped mirror *New J. Phys.* **10** 095017

[27] Kippenberg T J and Vahala K J 2008 Cavity optomechanics: back-action at the mesoscale *Science* **321** 1172
[28] Saulson P R 1990 Thermal noise in mechanical experiments *Phys. Rev.* D **42** 2437
[29] Mancini S, Vitali D and Tombesi P 1998 Optomechanical cooling of a macroscopic oscillator by homodyne feedback *Phys. Rev. Lett.* **80** 688
[30] Cohadon P F, Heidmann A and Pinard M 1999 Cooling of a mirror by radiation pressure *Phys. Rev. Lett.* **83** 3174
[31] Abramovici A *et al* 1992 LIGO: The Laser Interferometer Gravitational-Wave Observatory *Science* **256** 325
[32] Abbott B *et al* 2009 LIGO: The Laser Interferometer Gravitational-Wave Observatory *Rep. Prog. Phys.* **72** 076901
[33] Pinard M, Cohadon P F, Briant T and Heidmann A 2000 Full mechanical characterization of a cold damped mirror *Phys. Rev.* A **63** 013808
[34] Genes C, Vitali D, Tombesi P, Gigan S and Aspelmeyer M 2008 Ground-state cooling of a micromechanical oscillator: generalized framework for cold damping and cavity-assisted cooling schemes *Phys. Rev.* A **77** 033804
[35] Braginsky V B and Khalili F Ya 1992 *Quantum Measurement* (Cambridge: Cambridge University Press)
[36] Danilishin S *et al* 2008 Creation of a quantum oscillator by classical control *Phys. Rev. Lett.* submitted (arXiv:0809.2024)
[37] Kimble H J, Levin Y, Matsko A B, Thorne K S and Vyatchanin S P 2002 Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics *Phys. Rev.* D **65** 022002
[38] Buonanno A and Chen Y 2001 Quantum noise in second generation, signal-recycled laser interferometric gravitational-wave detectors *Phys. Rev.* D **64** 042006