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Observation of Mechanical Nyquist Noise in a Cryogenic Gravitational-Wave Antenna*

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A 680-kg, Weber-type, cylindrical, gravitational-wave detector has been operated at liquid helium temperature. The average vibrational energy in the lowest longitudinal mode at 1315.3 Hz was found to be consistent with the level of thermal noise at the antenna temperature. An effective noise temperature of 0.39 K for pulse excitation was measured. This is a factor of 20 below the lowest published values for room-temperature detectors.

The sensitivity of currently operating gravitational radiation detectors is limited by thermal noise in the antennas which are maintained at temperatures of about 300 K. In this Letter we report preliminary measurements made on an antenna cooled to liquid helium temperature. The observed minimum noise level corresponds closely to that expected at the lower antenna temperature, demonstrating for the first time that improved detectors can be made using cryogenic techniques. These results differ from those of another experiment in which an antenna at 4.2 K showed a noise temperature of 13 K.[1] Our experiments also confirmed the usefulness of a new, low-noise, superconducting, motion transducer. The presence of intermittent mechanical noise in the cryostat precluded meaningful measurements of the flux of gravitational radiation.

The detector has been described elsewhere[2]; a simplified schematic diagram is shown in Fig. 1. An aluminum antenna 0.4 m in diameter, 2 m long, and covered with a 0.4-mm sheet of superconducting Nb-Ti is levitated by a magnetic field of 0.2 T. The magnetic support provides an acoustic isolation of about 60 dB between the antenna and the cryostat. Since the transfer of liquid helium into the cryostat disturbs the antenna, the apparatus is arranged to provide a 14-d operating time between transfers.

The transducer consists of a tunable acceler-

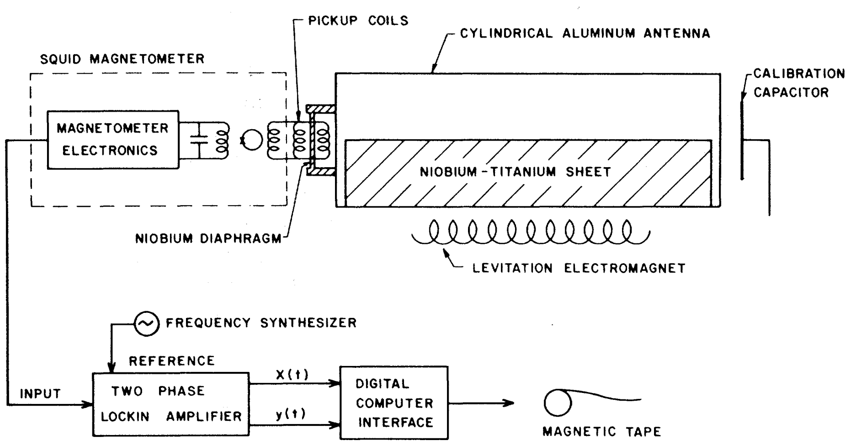

FIG. 1. Schematic of gravitational-wave detector and data-processing system.

ometer[3] mounted on one end of the antenna. The accelerometer comprises a superconducting niobium diaphragm with flat superconducting pick-up coils facing its two sides. The coils are connected in parallel to the input of a superconducting magnetometer biased at 30 MHz. The diaphragm serves as a high-Q mechanical resonator whose motion modulates the inductance of the pick-up coils which carry a persistent current. The magnetometer input current is proportional to the displacement of the diaphragm from its equilibrium position. The diaphragm self-resonance frequency is slightly lower than the antenna frequency, and the two oscillators form a two-normal-mode system with a frequency separation of 20 Hz. The output of the magnetometer is fed to a two-phase lock-in amplifier whose reference signal is derived from a frequency synthesizer. The in-phase and quadrature outputs, $x(t)$ and $y(t)$, are smoothed by low-pass filters, sampled, and digitally recorded as functions of time for subsequent analysis.

To allow calibration of the system two capacitor plates, each of area 0.05 m^2, were fixed facing the ends of the antenna at a separation of 5 mm. In order to determine the detector output corresponding to a known antenna energy, bursts consisting of a fixed number of sinusoidal cycles at half the antenna frequency were applied to the capacitor plates. The calibration burst was typically between two and three orders of magnitude shorter than the energy decay time of the antenna modes.

Figure 2 shows a typical calibration pulse and the resulting detector output, displaying the beating of the two excited normal modes. The measured sensitivity calibration based on the analysis of about fifty pulses of various lengths and voltages is in agreement with that calculated on the basis of known detector parameters to within the expected uncertainty of ±15%.

Data acquisition was carried out for consecutive periods of about 10 h spaced over several days. The output at the higher normal-mode frequency, which is dominated by antenna motion, was examined by setting the lock-in reference to within 0.01 Hz of the corresponding frequency, 1315.3 Hz. The lower mode output, which is dominated by diaphragm motion, was rejected by the chosen post-detection time constant of 0.3 s. The output was processed to obtain the signal power $E(t)$, where

$$E(t) = x^2(t) + y^2(t). \quad (1)$$

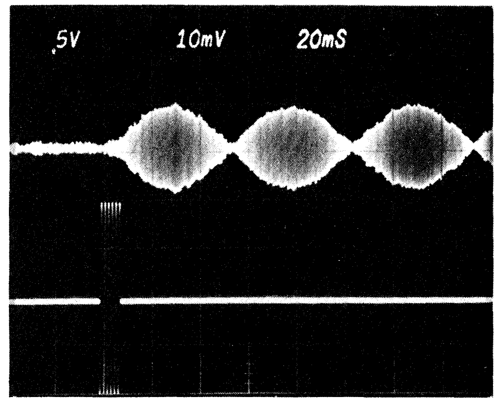

FIG. 2. Oscilloscope traces of a typical voltage pulse applied to the calibration capacitor plates (lower trace) and the subsequent accelerometer response (upper trace).

An analog time recording of $E(t)$ generally showed long periods of uniformly low noise level disturbed by comparatively intense bursts lasting for several minutes. The outputs of piezoelectric strain transducers attached to the cryostat showed that the noise bursts were correlated with periods of unusually high acoustic noise. The relative signal levels observed during the noise bursts showed conclusively that the antenna was being excited by the cryostat, rather than both being affected by gravitational radiation.

In the absence of transducer noise, the quantity $E(t)$ is proportional to the vibrational energy in the antenna mode. The constant of proportionality was determined from the calibration experiments and was used to reduce the recorded values of $E(t)$ to antenna energy. The measured probability distribution of $E(t)$ over a 10-h period during which the antenna temperature was 4.4 K is shown as the upper curve in Fig. 3. The contribution of broad-band noise was determined by setting the lock-in reference oscillator away from the normal-mode frequency and repeating the data-taking procedure: It was found to be less than 1%. If $E(t)$ were due only to mechanical Nyquist noise in the antenna, its distribution would be given by $\exp(-E/k_B T)$, where k_B is Boltzmann's constant and T is the temperature. The distribution function shown in Fig. 3 deviates from an exponential at high energies as a result of the short periods of intense noise discussed above. From the data at low energies it is clear that the primary component of the signal is consistent with Nyquist noise. The slope of the distribution function at low energies corresponds to a temperature

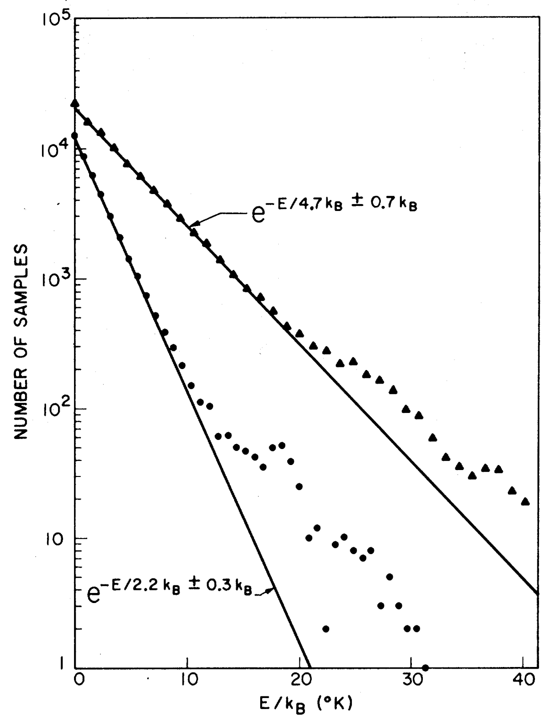

FIG. 3. Sample distribution of antenna vibrational energy E for 10 h of data with the system at a temperature 4.4 K (triangles), and 4 h of data with the system at 2.1 K (dots). The departure of the data at high energies from an exponential curve is discussed in the text.

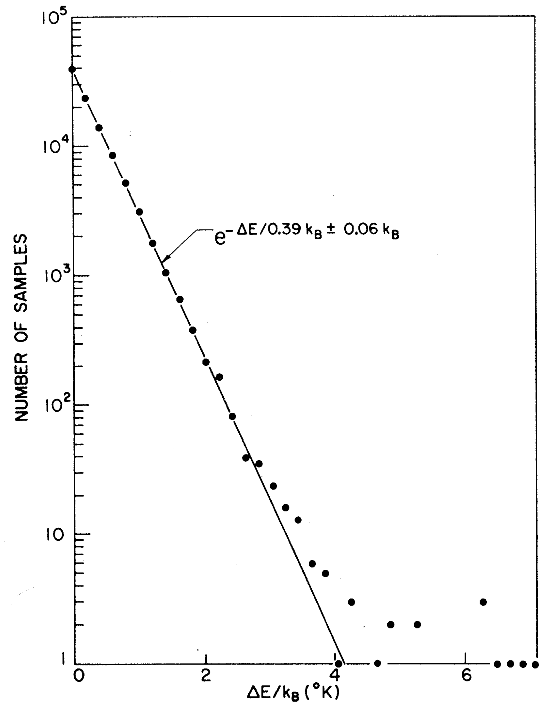

FIG. 4. Sample distribution of impulse energy ΔE for 10 h of data with the system at a temperature of 4.4 K. The departure of the data at high energies from an exponential curve is discussed in the text.

of 4.7 ± 0.7 K, the error arising mainly from the calibration uncertainty.

When the antenna was cooled to 2.1 K, the results shown in the lower curve of Fig. 3 were obtained. The low-energy data correspond to a temperature 2.2 ± 0.3 K.

In order to determine the decay time of the normal-mode oscillations, the correlation function $C(\tau')$ was calculated, where

$$C(\tau') = \langle x(t)x(t+\tau') + y(t)y(t+\tau')\rangle , \qquad (2)$$

and $\langle\rangle$ denotes a time average over the data run. It was found that the amplitude decay time of the mode was 16 s.

In order to approach the condition required to detect short pulses of gravitational radiation, the data were processed to obtain the quantity $\Delta E(t)$, where

$$\Delta E(t) = [x(t) - x(t-\tau)]^2 + [y(t) - y(t-\tau)]^2, \qquad (3)$$

using a differencing time τ of 0.3 s. The probability distribution of ΔE is shown in Fig. 4. The average $\langle \Delta E\rangle$ can be referred to as an impulse energy and, for the data shown, has a mean value corresponding to a temperature of 0.39 ± 0.06 K. This value includes a correction factor to take into account the attenuation of pulse excitations by post-detection filtering and differencing and is consistent with the value calculated from the correlation data.[4]

The measured values of antenna energies agree with the respective antenna temperatures to within the experimental accuracy, showing that the lowest longitudinal mode has been successfully cooled to helium temperature. The agreement also shows that, with the detector parameters used, noise fed back from the magnetometer into the antenna does not increase the mode temperature by more than 0.3 K. Together with the observed level of wide-band magnetometer noise, this places an upper limit of 0.05 K on the magnetometer noise temperature. This figure is consistent with the lower limit of 0.01 K estimated for the magnetometer from parametric amplifier theory.

The quantity $\langle \Delta E\rangle$ represents the noise background over which pulse excitations of the antenna must be detected. If the simple differencing algorithm had been replaced by the optimum linear algorithm for pulse detection,[5] calculations show that the average impulse energy would have been $k_B \times (0.24\ \text{K})$. The lowest published value for room-temperature gravitational-wave detectors is $k_B \times (7.3\ \text{K})$.[6]

For the data presented in this paper the decay time of the antenna mode was reduced by a defective accelerometer mounting. This has since been replaced, increasing the decay time by about an order of magnitude. Steps are also being taken to remove all sources of spurious noise. With these modifications, it should be possible to achieve an average impulse energy of $k_B \times (0.02\ \text{K})$ with this antenna and transducer. If two such antennas were operated in coincidence, unpolarized gravitational radiation pulses of energy spectral density 60 J m^{-2} Hz^{-1} could be detected with an accidentals rate of 1 per day. The comparable spectral density for current room-temperature detectors[7] is 10^4 J m^{-2} Hz^{-1}.

These experiments have demonstrated that cryogenic gravitational wave antennas and transducers are practical. Work is proceeding on a 4500-kg antenna system using a microwave-pumped magnetometer. With this it should be possible to obtain a sensitivity approaching the ultimate limit for linear detectors.[8]

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Observation of Prompt Single Muons and Dimuons in Hadron-Nucleus Collisions at 200 GeV/*c**

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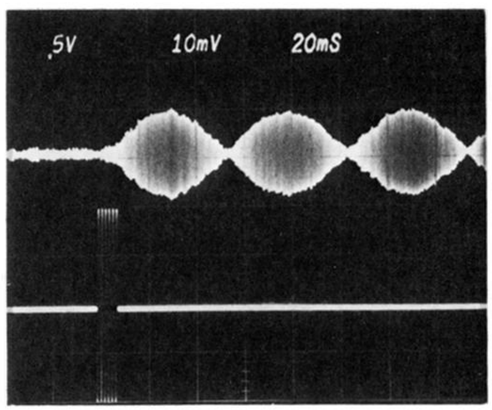
We trigger a large-acceptance spectrometer by single muons and observe any additional muons with good efficiency. The effect of π and K decays is subtracted to obtain the prompt muon signal in the kinematic region $0.1 < x < 0.4$ and $p_T < 1.0$ GeV/c. We find 0.7 ± 0.2 of all prompt μ's are produced in pairs; the μ/π ratio decreases with x but increases with p_T, averaging 3×10^{-5}.

In a previous Letter[1] we have considered the contribution of muon pairs to the yield of single prompt muons and concluded that this contribution is large. In that work, only muon pairs were observed, and the corresponding inclusive single muon yield was obtained by a calculation. As part of our experimental program at Fermilab, we performed a short experiment in which the large-acceptance University of Chicago cyclotron magnet spectrometer was triggered by the production of a single muon, and any additional muons were detected with high probability. In this way we directly approach the important question: Are prompt muons produced in pairs?

The first works[2,3] to confront this question were based on estimates of prompt muons from decays of vector mesons; they concluded this source is insufficient to explain all prompt muons. Including the effect of the experimentally observed continuum of dimuons, we have been able to account for the bulk of the prompt single muons.[1] Leipuner *et al.*[4] observed both single muons and dimuons, concluding that the latter explain the former although the acceptance of the apparatus was such that the pairs-to-single ratio was 1/10.

Prompt muons are defined as those not result-



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