Measuring gravity on the smallest scales

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Gravity, although the weakest among the fundamental forces, poses significant questions in modern physics. It remains unexplained in the context of the standard model and appears to be disconnected from quantum theory. To tackle this issue, it is crucial to test gravity at small scales where quantum effects become significant. In this study, we have successfully demonstrated the gravitational coupling between two 1 mm gold spheres and mapped the gravitational force by modulating the source mass position. We observed both linear and quadratic couplings due to the potential's nonlinearity. By extending gravity measurements to even smaller source masses and low gravitational field strengths at the Conrad Observatory, our work will enable us to investigate fundamental interactions and explore quantum gravity in the near future.

Figure 1 depicts the experiment using two gold spheres: one acts as the gravitational source with a radius of $R = 1.07 \pm 0.04$ mm and a mass of $m_s = 92.10.1$ mg, while the other serves as the test mass with a mass of $m_t = 90.70.1$ mg.

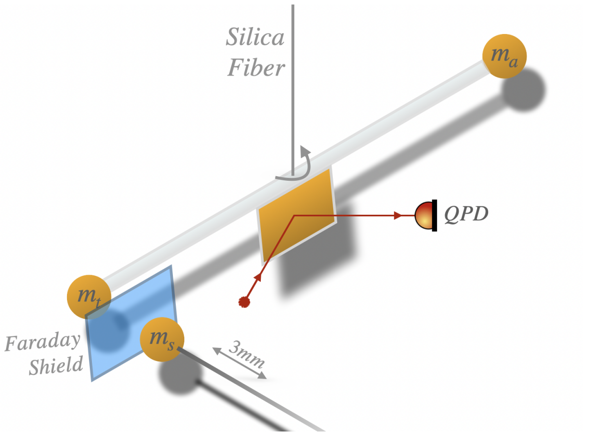

Figure 1: A torsion pendulum consisting of two gold spheres. One serving as a test and the other as a counterbalance and suspended by a 4-µm-diameter silica fiber. The torsion angle is measured by an optical lever directed to a quadrant photodiode. The gravitational interaction is modulated by a harmonically moving source at a frequency of 12.7 mHz. Direct electrostatic coupling is suppressed by a Faraday shield. ©Mathias Dragosits

The source mass generates a time-varying gravitational potential at the test mass location through periodic modulation of its position. To minimize noise, the acceleration of the test mass is measured in a torsion pendulum configuration at a pressure of 6×10^{-7} mbar. The angular deflection of the pendulum is optically monitored, and the displacement time series is de-convoluted with the inverse of the mechanical susceptibility to obtain the corresponding force spectrum. Electrostatic forces are minimized by grounding the source mass to the vacuum chamber, shielding the test mass with a conductive Faraday shield, and mitigating charges using ionized nitrogen. The geometric separation of the masses is determined with an accuracy of 20 µm, and the distance is varied between 2.5 mm and 5.8 mm. To minimize other influences on the test mass, such as seismic, acoustic, and magnetic noise, shielding and other measures are implemented. Despite low-frequency gravitational noise of urban origin, the experiment detects test-mass accelerations at frequencies of up to 0.1 Hz at a sensitivity better than 2×10^{-11} ms^{-2} within half a day of measurement.

We modulate the position of the source mass at a frequency well above the fundamental torsional pendulum resonance, resulting in a free-mass response. According to Newton's law, the source mass generates a gravitational acceleration on the test mass. We confirm this gravitational interaction by measuring the force spectrum of the test mass. By correlating the measured separation between the source and test masses with the independently inferred force, we obtain a position-dependent mapping of the gravitational force. Our experiment yields a coupling constant of G = $(6.04 \pm 0.06) \times 10^{-11}$ $m^3kg^{-1}s^{-2}$. We detect deviations from the CODATA value for Newton's constant by around 9%, which is fully covered by the known systematic uncertainties in our experiment. Our measurements demonstrate gravitational coupling between a test mass and a 90 mg spherical source mass. This is the smallest single object whose gravitational field has been measured to date, with non-gravitational forces contributing less than 10% of the observed signal. Our experiment opens up the possibility of probing the gravity of objects even smaller than the Planck mass, with the potential of going considerably smaller by using miniature torsion pendulums with improved thermal noise. However, anthropogenic low-frequency noise sources need to be understood and mitigated to improve the sensitivity of such experiments.

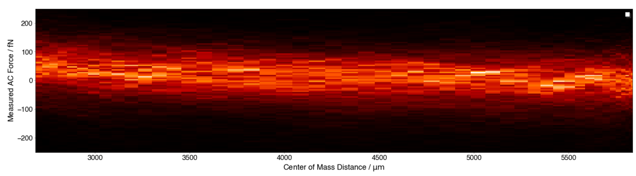

Figure 2: The force exerted versus source-test mass separation displays spatial nonlinearity of the source-mass potential. The actual measurement precision is apparent from the extracted mean force and its standard deviation obtained by bootstrapping.

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