A NEW METHOD FOR TESTING NEWTON'S GRAVITATIONAL LAW

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ABSTRACT

We report on a new experimental method for determining the gravitational force of a laboratory test mass on a Fabry-Perot microwave resonator. The resonator consists of two Fabry-Perot mirrors suspended as pendulums. Changes of $2 \cdot 10^{-11}$ m in the pendulum separation can be resolved as a shift of the resonance frequency of the resonator. This limit corresponds to an acceleration of $7 \cdot 10^{-11}$ m s^{-2} of one mirror with respect to the other. In a first experiment we have measured the gravitational acceleration generated by a 125 kg test mass as a function of distance in the range of 10 to 15 cm and tested Newton's gravitational law with an accuracy of 1 %. No deviation is found. Furthermore, the gravitational constant G is determined with similar precision.

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Newton's law of gravitation has recently been tested in a series of new experiments with different precision. These experiments were stimulated by reports on observations of possible short-range deviations from Newton's square law[1-4]. In this context it also becomes of great interest to improve on the uncertainty, with which the gravitational constant G is known experimentally. The smallest relativ error achieved so far is $1 \cdot 10^{-4}$. However, different experiments disagree in their results outside of the quoted errors[1,2].

This discussion has motivated us to develop a pendulum gravimeter to measure the gravitational acceleration of a test mass as a function of distance and to determine the gravitational constant.

I. THE FABRY-PEROT GRAVIMETER

The gravimeter consists of two Fabry-Perot mirrors[5]. They are separately and bifilar suspended as pendulums with a length of $l=3$ m (Fig. 1) at a distance of 15 cm. The gravitational acceleration of a 125 kg test mass elongates both pendulums. The change of the pendulum distance, which is to be measured, is proportional to the difference of the accelerations of each pendulum. It is calculated from a numerical integration of Newton's square law over the mass distribution of test mass and resonator. The distance between the centers of test mass and of the pendulum next to the test mass is varied from 10 - 15 cm and leads to a change of the mirror distance of $25 \cdot 10^{-9}$ m. This gravitational effect is to be measured by means of the frequency shift of the Fabry-Perot resonator.

A quality factor of the resonator of 140 000 is obtained experimentally. The width of the resonance curve corresponds to about 1 µm. A shift of the resonance frequency $2 \cdot 10^{-5}$ times smaller than the width of the resonance curve can be detected, which corresponds to a displacement of $2 \cdot 10^{-11}$ m.

In order to cancel out disturbing effects, both mirrors are suspended as pendulums of equal length. The most important effects are: pendulum oscillations forced by microseismic vibrations of the ground; tidal forces; disturbing gravitational forces of masses in the surrounding of the apparatus; movements and tilts of the ground, etc.

The whole experiment is build up in a vacuum tank to avoid dielectric effects, convection and gas pressure forces. In order to keep thermal expansion effects small, the vacuum tank is build with good thermal insulation.

II. RESULTS OF GRAVITATIONAL MEASUREMENTS

The gravitational force between the test mass and the Fabry-Perot resonator was measured by moving the test mass periodically from the position, for which the gravitational force is to be determined, to a reference position. This procedure results in a modulation of the resonator frequency.

The modulation amplitude is determined by means of a Fourier analysis or a demodulation technique. Statistical errors, high- and low-frequency noise (corresponding to 0.1 nm) and drift effects (0.1 - 0.5 nm / h) can be separated with this procedure and the gravitational force is determined with high accuracy (the statistical error corresponds to 0.02 nm).

The modulation procedure has been repeated with the test mass in different positions, and the shift of the pendulum distance has been measured as a function of distance between resonator and test mass (Fig. 2). On the level of 1% (dominated by systematical errors) no significant deviations from Newton's gravitational law are seen and there is no indication of a fifth force with a range of a few centimeters.

The gravitational constant is determined from six measurements to be

$$G = (6{,}66 \pm 0{,}06) \cdot 10^{-11} \text{ N m}^2 \text{ kg}^{-2} \qquad (1)$$

The quoted error is the statistical error, determined from the measured data. Systematic errors of about 2% have to be added. However, the result is in good agreement with the CODATA-value of the gravitational constant.

III. SUMMARY AND OUTLOOK

We have successfully tested a new method to measure the gravitational force of a test mass as a function of distance in the range of a few centimeters. The present sensitivity is sufficient to measure the gravitational force with an accuracy of about 10^{-3} at various distances and to determine the gravitational constant with an accuracy of about $2 \cdot 10^{-4}$. Furthermore, it should be possible to increase the sensitivity of the resonator using superconducting mirrors by more than two orders of magnitude[5)]. Certainly, the errors in measurement of the gravitational force are not yet limited by the resolution due to the normal conducting resonator. Consequently, we try to improve the experimental set-up and investigate Newton's gravitational law in the range of 0.5 - 2 m.

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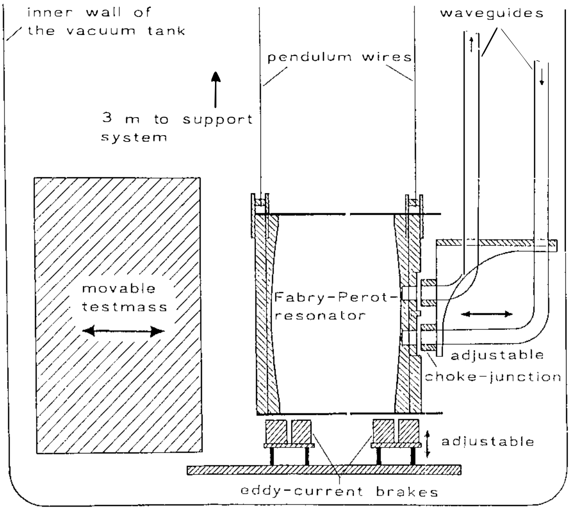

FIG. 1. Schematic diagram of the inner part of the vacuum tank with the Fabry-Perot resonator and the test mass. To scale: mirror distance = 14 cm.

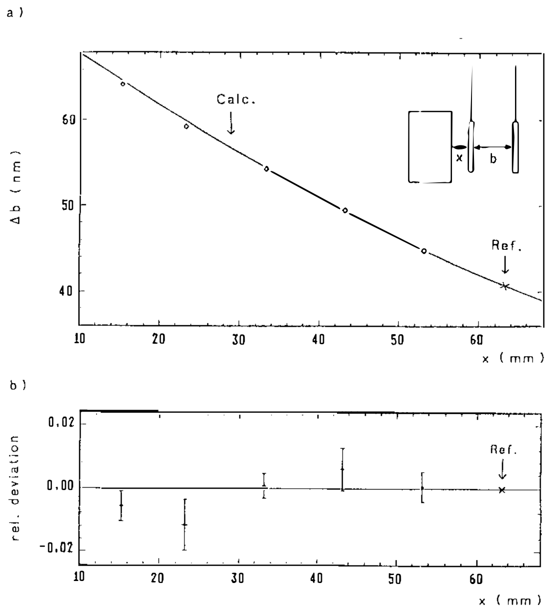

FIG. 2. The shift Δb in the mirror separation due to the gravitational force vs. the distance between test mass and resonator is shown in (a). The full line is a least-squares fit to the data which is obtained by a numerical integration of the gravitational force over the mass distribution. (b) shows the relative deviation of the experimental data in more detail.