Search for millicharged particles using optically levitated microspheres

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Abstract:

We report results from a search for particles with charge q > 5 x 10^{-5} *e* in bulk matter using optically levitated microspheres in high vacuum [1]. No evidence for such particles was observed in a total mass of 1.4 ng, which gives an upper limit on the abundance per nucleon, $n_\chi < 2.5 \times 10^{-14}$ at the 95% CL. These results provide the first direct search for millicharged particles bound in macroscopic quantities of bulk matter with sensitivity to a single particle with charge < 0.1 *e*. They also provide the first demonstration of a search for new interactions or particles using optically levitated dielectric microspheres in high vacuum. Future improvements to these techniques may also significantly increase sensitivity to other short range forces, including non-Newtonian gravitational forces at micron distances.

Millicharged particles:

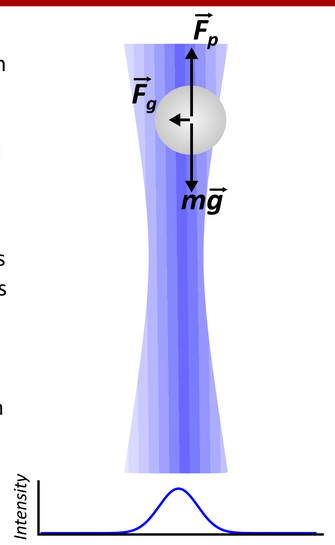
"Millicharged particles" are defined as particles with charge q = εe for ε << 1. Such particles have been proposed in extensions to the Standard Model that include new, weakly coupled gauge sectors (e.g. [2]). It is possible that millicharged particles are a component of the universe's dark matter [3]. If such particles exist, they could have been produced in the early universe and may have formed stable bound states that can be searched for in terrestrial matter today [4].

Constraints on millicharged particles exist from astrophysical and cosmological observations, as well as laboratory searches [5]. However, these measurements are typically insensitive to particles with mass m_χ > 1 GeV. Searches in bulk matter can probe these higher masses, but suffer from significant uncertainty in the relic density of such particles in terrestrial materials [4]. Previous bulk matter searches using magnetic levitometers [6] or high-throughput Millikan oil drop techniques [7] had sensitivity to single particles with ε > 0.1.

Optical levitation:

This work uses 5μm diameter silica microspheres that are optically trapped in a vertically oriented laser beam [8]. This configuration allows the microsphere to be stably trapped by the optical potential in all 3 degrees of freedom (DOF).

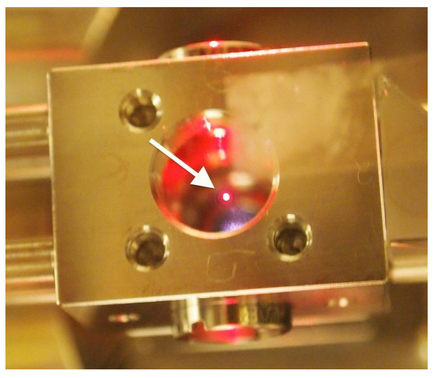
The equilibrium along the beam axis is determined by the height above the focus where the radiation pressure, $\vec{F_p}$, balances the weight of the microsphere. In the radial directions, the intensity gradient in the Gaussian beam provides a restoring force, $\vec{F_g}$, in the direction of the maximum intensity.



Schematic of the optical levitation technique used in this work. A 5μm diameter silica microsphere is optically trapped in a vertically oriented laser beam.

At high vacuum pressures, residual dissipation due to gas collisions becomes small, and monitoring the microsphere's position in 3D allows sensitive force detection [9].

However, the trap is not stable below pressures ~0.5 mbar, where the residual gas can no longer dissipate the mechanical heating of the microsphere's motion by the trapping laser. At these pressures, active feedback of the optical potential based on the microsphere's position is necessary to maintain a stable trap [10]. We have demonstrated stable trapping of a single microsphere for >100 hours at ~10^{-7} mbar.

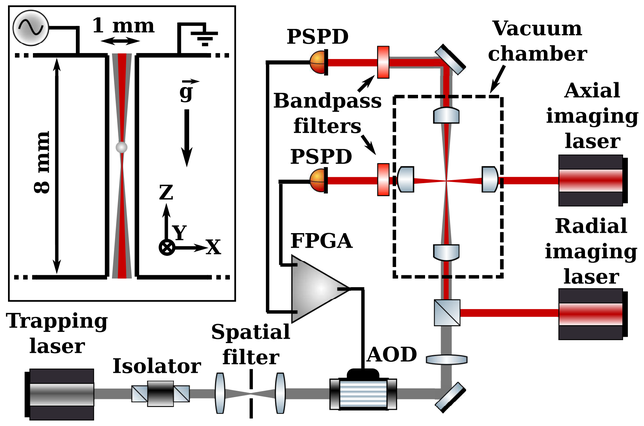


Photograph of a trapped microsphere in vacuum. The arrow denotes the microsphere, which is illuminated by a red imaging laser.

Experimental setup:

Microspheres are levitated by a λ=1064 nm diode laser, which passes through an acousto-optic deflector (AOD) before entering the vacuum chamber. The optical trap is surrounded by the flat faces of two cylindrical electrodes.

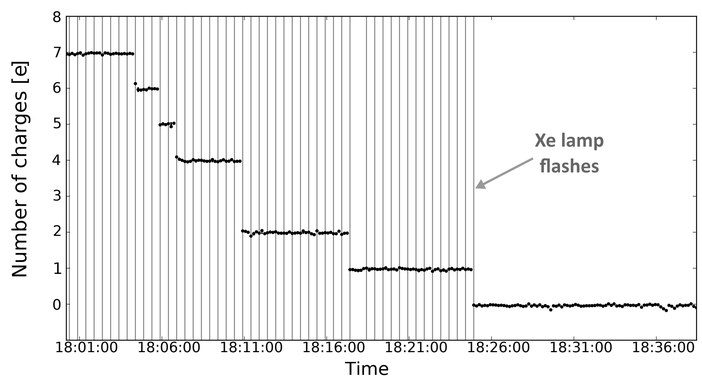
The position of the microspheres is monitored using two orthogonal imaging beams, and the light transmitted by the microsphere is imaged onto two position sensitive photodetectors (PSPDs). An FPGA provides feedback signals used to modulate the AOD, which cools the mechanical motion of the microsphere at low pressure.



Schematic of the optical layout. The inset shows a cross-sectional view of the electrodes surrounding the trap.

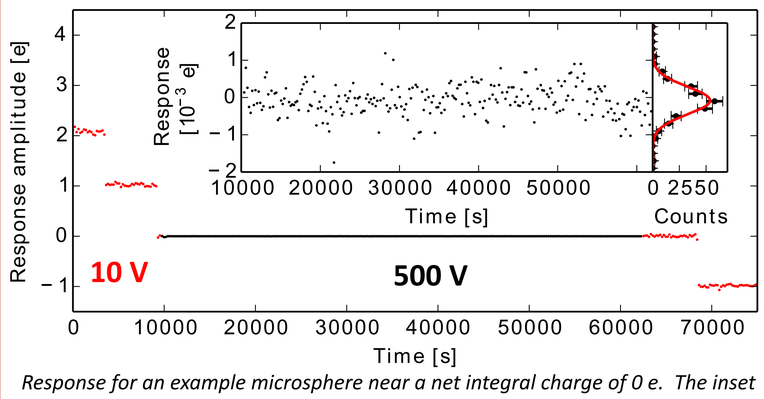
Calibration and data taking:

Microspheres typically have a net charge from 100-1000 *e* after the loading process. This charge is measured by applying an AC voltage to the electrodes surrounding the trapping region and measuring the response of the microsphere motion. To discharge the microspheres, a Xenon flash lamp is used to illuminate the electrodes, producing e^- that can be captured on the microsphere. After discharging to a net charge < +10 e, the drive amplitude is increased to 10 V, which is sufficient to observe single electron steps in the net charge with high signal to noise.



Example of discharging process from a net integral charge of +7 e to 0 e.

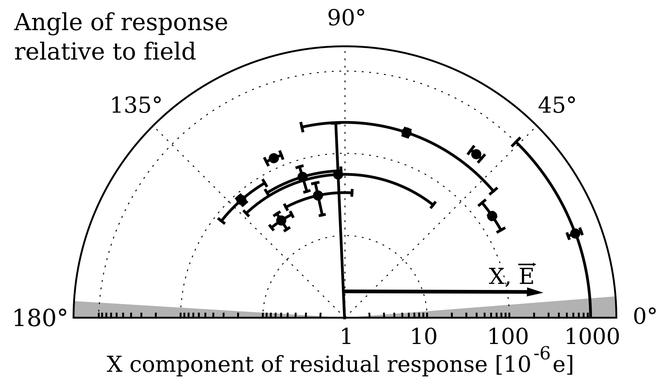
For each microsphere, the response is calibrated using the observed single e^- steps. Once the microsphere is neutralized, the drive amplitude is increased to 500 V, and data are taken for ~5 x 10^4 s. The voltage is then decreased to 10 V, and the microsphere is recharged to -5 *e*, to provide additional calibration data.



Response for an example microsphere near a net integral charge of 0 e. The inset shows a zoomed-in view of the 500 V data.

Results and limits:

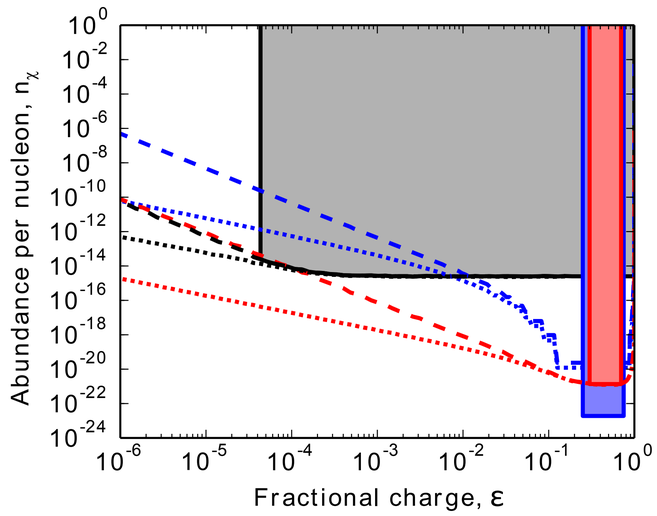
The residual response at a net charge of 0 *e* was measured for a total of 10 microspheres to quantify variations between microspheres and increase the total mass tested. The resulting residual response in the direction of the electric field is shown below.



Measured component of the residual response in the direction of the electric field and the angle of the total response relative to the field for each microsphere.

While the microspheres show a statistically significant residual response, the angle of the residual motion is typically offset from the electric field by 45-90°. In contrast, the calibration data all show a response aligned within 5° of the field (gray band). Given the offset of the measured response angle relative to the expected response, the non-zero residual does not provide evidence for a non-zero millicharge.

We conservatively calculate limits on the abundance of millicharged particles by assuming that the component of the residual response in the direction of the electric field could be due to a net fractional charge. Below the single particle threshold, limits are calculated assuming either that the average number of positive and negative particles is equal (dashed) or that only a single sign of such particles is trapped in bulk matter (dotted).



Limits on the abundance of millicharged particles per nucleon versus the fractional charge. The results from this work (black) are compared to previous results from magnetic levitometers [5] (red), and from Millikan oil drop techniques [6] (blue). The filled regions show the 95% CL exclusion limits where each experiment has sensitivity to a single fractional charge, while the lines show the calculated exclusion limits below the single particle threshold assuming equal average numbers of positive and negative particles (dashed), or only a single sign of particles (dotted).

References:

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