**Topical: The Nature of Nothing: Exploring the quantum vacuum in microgravity**

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# Introduction (Nothing matters…)

Even space devoid of both matter and radiation still pulsates with zero-point energy according to the laws of quantum mechanics. The nature of this quantum vacuum appears to lie at the heart of several of the greatest mysteries in modern physics, including the incompatibility of quantum theory and general relativity, the cosmological constant problem, cosmic inflation, and the nature of dark energy.[1] As an example of our lack of understanding in this area, an oft-quoted elementary calculation of the cosmological constant based on summing the zero-point energy density of electromagnetic modes with a high energy cutoff at the Planck energy leads to a rather embarrassing 120 orders of magnitude discrepancy between calculated and measured values. A more rigorous calculation, it should be mentioned, reduces this discrepancy to a mere factor of 1055[2] thus resulting, one supposes, in a 65 orders of magnitude reduction in embarrassment, and yet still remains far from satisfactory.

Despite its mysteries, the quantum vacuum produces real physical manifestations that can be observed and precisely measured. These include forces which often must be accounted for (and perhaps may be exploited) in applications of nanotechnology. It leads to the famous Lamb shift of atomic energy levels, and as well to the familiar phenomena of spontaneous emission. In this paper, we will discuss a variety of experiments involving cavity quantum electrodynamics, “quantum engineered” vacuums, and measurements of vacuum induced forces, each of which can potentially benefit from the microgravity environment.

# Measurements of Casimir-Polder force

The Casimir-Polder (CP) force describes the interaction of an atom with a nearby dielectric surface, and includes a significant contribution from vacuum fluctuations. It is closely related to the more well-known Casimir force [3] which produces an attractive force between bulk objects such as two dielectric plates, and arises from the net effect of the enhancement of vacuum fluctuations resonant with the plate spacing, and the inhibition of those that are not resonant. For atoms in the ground state, the CP force is also attractive, though for atoms in an excited state, it can have an oscillatory sign as a function of distance [4]

Recent studies of the CP force using Bose condensates confined near surfaces [5] have yielded measurements at the few percent level. Already, results at this accuracy have been claimed to constrain possible theories involving extra dimensions [6] Moreover, inaccuracies of our knowledge of exotic short-range forces can also be limited by our knowledge of the CP force.

Precisely controlled, ultra-cold atoms such as those produced by the Cold Atom Lab [7,8] provide exquisite local sensors of the electromagnetic quantum vacuum. While several schemes have been proposed or utilized to measure the CP force on Earth, a technique that is particularly suitable for microgravity utilizes atom interferometry, which has already been demonstrated on the CAL instrument [9] Our scheme would involve an atomic sample prepared with a slight drift velocity relative to a surface of interest. A four pi/4 pulse interferometer is employed, with two pulses administered on one side of the sample, with a first pulse preparing atoms in a superposition, with one arm brought into the vicinity of a well-characterized surface. A second pulse brings the velocity of the packets normal to the surface to a standstill. The wave packets then drift past the surface, where a third pulse is used to close the arms of the interferometer, while a fourth recombines the packets. Phase shifts can then be obtained as a function of distance from the surface, and length of time near the surface. As described, this scheme would require a high degree of vibration isolation, but one can also envision more complex schemes involving two atomic species or multiple interferometer paths (though we should also note that microgravity offers the possibility of near perfect vibration isolation).

Any experiment requiring ultra-cold atoms as a local probe will face a tradeoff between the need for lower temperatures (which allow for longer observation times and better position control), and the fact that atomic samples necessarily become more delocalized as you cool them. Using heavier atoms is helpful, but these types of experiments may benefit from novel sources such as quantum droplets, a self-localized state of quantum matter consisting of a superfluid mixture stabilized against collapse by quantum fluctuations.[10]

# Anderson localization of matter-waves arising from CP force

For complex surface geometries, lateral CP forces can be induced along with those normal to the surface. This allows for the possibility for the development of “quantum engineered” vacuums, which may one day find utility in nanotechnology applications [11], but are also of interest for the study of fundamental phenomena such as Anderson localization, the absence of diffusion of waves moving through a disordered medium [12] This effect, along with its precursor, weak localization (characterized by an enhancement of backscattering from a disordered potential) is essential for understanding the dynamics of electrons moving through a semiconductor with sufficient amounts of defects or impurities, but has also been observed for light moving though random media [13,14,15] and atomic matter-waves moving through disordered potentials produced by laser speckle. [16]

Calculations of the expansion of a radially confined Bose condensate near a rough, disordered surface show clear evidence of localization, with the density of the condensate falling algebraically rather than exponentially in this quasi-1D case. [17] Microgravity relieves the need for radial confinement, allowing such studies to be extended to include expansion in random 2D and 3D potentials. Here we expect the sensitivity to disorder to be less than the 1D case, however the remarkably low temperatures and long observation times available in microgravity should allow these phenomena to be explored with great resolution.

# Confining atoms with vacuum forces

Engineered quantum vacuums have also been invoked as a way to confine atoms using purely vacuum forces. Here a dielectric surface with a tailored emissivity has been shown to provide a strong trapping force for atoms dressed by a weak external optical field. The ground state is attracted to the surface while the excited state experiences a potential that can be engineered to be resonantly enhanced and repulsive, forming, in the simplest geometry, a 1-dimensional atomic waveguide just a few nanometers from the surface. With an optimal design the excited state fraction can be arbitrarily small. [18] While the forces exerted on the atoms can be much stronger than gravity, microgravity will still dramatically facilitate the observation of such traps due to the remarkable levels of cooling and control over atom position that can be achieved in microgravity, along with the much weaker forces need to confine a sample. While the observation of atoms trapped by vacuum forces would be remarkable in and of itself, such traps may find utility as probes of surface physics or as remarkably sensitive sensors of vacuum forces.

An earlier proposal to trap atoms with vacuum, employing Rydberg atoms in super conducting cavities, was developed by the Haroche group [4] Here atoms prepared in an excited state before entering a resonant cavity can be shown to reflected or trapped by the mechanical force arising from the reversible exchange of a single excitation between the cavity (originally in its vacuum state) and the atom. Remarkably the effect is significant even at microwave energies, though, as noted by the authors, would almost certainly require reduced gravity to observe.

# Directed and Suppressed spontaneous emission

The spontaneous emission rate of an atom is proportional to the density of emission modes available to the atom and can be enhanced or inhibited by placing the atom within a high finesse cavity resonator with a volume of the order of the wavelength, or alternatively in a confocal cavity with a large number of degenerate modes, and subtending a large solid angle. These changes to spontaneous emission have been observed in a number of experiments. [19]In microgravity atoms can be positioned within cavities very precisely, released with exceptionally small residual velocity, and observed for long periods. Taken together these features should allow dramatic increases in the observed levels of spontaneous emission suppression.

For very high finesse, small volume, cavities it is possible for the coupling into a single mode of the cavity to dominate over both emission into all other modes and also cavity dissipation. In this strong coupling regime, a single atom can be observed to reversibly exchange a single photon with the vacuum. [20 ]Light transmitted from such an atom cavity can be shown to be highly nonclassical, and nonlinear optical effects can be observed with single atoms and a fraction of a photon. [21,22]

Once again, it would be interesting to revisit these experiments in microgravity, where precisely positioned atoms can be observed for long times. Mechanical effects on the atom’s motion would be of particular importance. A simple example of this would be directed spontaneous emission: an atom launched with a velocity component along the axis of a slightly detuned cavity will preferentially emit its photon in one particular direction. This results in an observable momentum kick on the atom, and an unprecedented demonstration of control over the spontaneous emission process.

# Implementation (Nothing to it…)

Several of the experiments proposed here could be carried out in a customized version of the Cold Atom Lab science module in which engineered surfaces are introduced into the vacuum system. A means of cooling these surfaces (to minimize the thermal contribution to the CP force) would be highly desirable, though not necessary for initial investigations. The configuration of AI beams would need to be changed to probe surface interactions. The cost of such a science module would likely be in the range of 3.5-4million (roughly the cost of the first CAL science module upgrade), a cost which could be shared between several compatible investigations (this cost does not include operations costs, nor funding to investigators). Experiments involving the interaction of ultra-cold atoms with optical or microwave cavities would need to await a second-generation instrument with a somewhat larger vacuum chamber. In general, however the current performance already achieved in CAL would support the science outlined here in terms of atom number, temperature, and position control. Atom interferometry experiments would benefit from a larger Bragg beam diameter. A short ground program is highly recommended to allow for optimization of the flight design for greatest scientific impact.

# Conclusion

We have outlined a number of studies relating to the quantum vacuum that would benefit greatly from a microgravity environment and that appear to require only a modest extension of our current space capabilities as demonstrated by the Cold Atom Lab. It is of course not obvious that any of these measurements will directly shed light on the great mysteries of physics discussed in the opening paragraph. However, we believe that this program would provide numerous compelling science results while capturing the public’s imagination and, perhaps, pointing the way to a new understanding of physics.

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