MEASUREMENT OF SHORT RANGE FORCES USING COLD ATOMS

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We describe the new project FORCA-G, which aims at studying the short range interactions between a surface and atoms trapped in its vicinity. Using cold atoms confined in the wells of an optical standing wave, the atom-surface potential will be measured with high sensitivity using atom interferometry techniques. The experiment will allow a test of gravity at short distances, which will put stringent bounds on a possible deviation from the known laws of physics. FORCA-G will also allow a measurement of the Casimir Polder interaction (QED vacuum fluctuations) with unprecedented accuracy.

Keywords: Casimir Force - Gravitation - Tests of fundamental Physics

1. Introduction

One of the frontiers of modern physics is the study of forces at very small length scales ($<$ 1 mm). Such length scales are the domain where quantum electrodynamics, QED, interactions (Casimir type forces) become important and where several recent theoretical ideas point to the possibility of new interactions related to gravity. All of physics is at present well described by the standard model that unifies three of the four fundamental interactions in nature. However, the unification of all four interactions (including gravitation) has so far proven elusive. Several recent astronomical observations indicate that our current understanding of gravitation might be incomplete or erroneous because to match those observations with present theory one has to invoke some form of additional matter and energy (dark matter and dark energy) that constitutes about 97% of the total mass of the universe. Consequently, it appears essential to experimentally test gravitation at all accessible length scales. In particular, unification theories suggest some deviations from the known laws of gravity at very short range.[1] Quite generally, such deviations from Newtonian gravity can be parameterized by a Yukawa type potential of the form $U = U_N(1 + \alpha e^{-\frac{r}{\lambda}})$ where U_N is the Newtonian potential and α and λ are the amplitude and range of the modification. Exclusion regions in the (α, λ) plane are provided by experiments scaling from laboratory size to the size of the solar system. Possible deviations are relatively well constrained over a large range of distances from a mm to the size of the solar system. However, two "open windows" remain at very small ($<$ 1 mm) and very large ($> 10^{15}$ m) range, the former being the focus of this experiment.

However, at distances below ~ 30 microns the gravitational force between two neutral objects is dominated by the Casimir force. For distances of this order or below it is then Casimir force measurements which give the strongest constraints for the existence of hypothetical new forces in the $(\alpha - \lambda)$ plane. After its prediction[2] in 1948, the Casimir force between two macroscopic objects has been observed in a number of "historic" experiments which confirmed its existence and main properties. More recent measurements with largely improved accuracy have allowed for comparison between measured values of the force and theoretical predictions at the few % level, some of them have also allowed to improve constraints in the $(\alpha - \lambda)$ plane. Shortly after the prediction of the Casimir force between two parallel plates, Casimir and Polder[3] predicted the analogous attractive force between an atom and a macroscopic plane surface. More generally, the Casimir-Polder potential ($1/r^4$ dependence on distance) is the retarded part of the total QED interaction between the atom and the surface. The non-retarded part, which is dominant at short distances, is known as the "Van der Waals" potential and has a $1/r^3$ dependence. Also, at non-zero temperatures (and larger distances), the overall QED potential becomes dominated by a temperature dependent term again with $1/r^3$ dependence. This leads to an interesting phenomenological behaviour with two distance dependent crossover points from $1/r^3$ dependence to $1/r^4$ and back. At 300 K the two crossover points are situated at a few tenths of a micron and a few microns respectively (depending on the atom and surface characteristics). These features give a lot of richness to the atom-surface interaction (rather than surface-surface), that can be explored at experiments at the micron and sub-micron scale like the one proposed here.

On the experimental side, measurements at distances ranging from 10^{-8} m to 10^{-3} m have been the domain of microelectromechanical systems and of torsion balance experiments. Two major difficulties of such mechanical experiments are the exact knowledge of the geometry of the setup (distance, surface roughness, etc...) and the precise measurement of the very small forces involved. An alternative that might provide a way around those difficulties is the use of cold atoms. The experiments that have been carried out so far all confirm the theoretical predictions from QED (Van der Waals and Casimir-Polder effect) at distances ranging from a few tens of nanometers to several microns, however, none of them have yet reached the uncertainties achieved by the best mechanical measurements. Typically, experiments measuring the atom-wall QED interaction have an overall relative uncertainty at or above 10 %.[4] In this project we pursue an original scheme, first described in 5, that has the advantage of providing accurate control of the distance and accurate direct measurement of the potential (rather than the force) between an atom and a macroscopic surface.

2. Principle of the experiment

Atoms are trapped in a vertical standing wave, created by a laser far detuned from resonance. The internal atomic structure is approximated by a two-level system, with two long lived states $|g\rangle$ and $|e\rangle$ with energy difference $\hbar\omega_{eg}$. The external hamiltonian $\hat{H}_{ext}$ (kinetic energy, trapping and gravitational potential) is identical for both $|g\rangle$ and $|e\rangle$. For sufficiently large depth U_0 of the trapping potential, Landau-Zener tunnelling can be neglected. The Eigenstates of $\hat{H}_{ext}$ are then the so called Wannier-Stark (WS) states $|W\rangle$. The discrete quantum number m is the "well index" characterizing the well containing the main peak of the wave function $\langle x|W_m\rangle$. The energy separation between adjacent states is simply the change in gravitational potential between adjacent wells: $\hbar\Delta_g = m_a g\lambda_l/2$, where g is the gravity acceleration. This leads to a Wannier-Stark ladder of Eigenstates. Transitions between $|g\rangle$ and $|e\rangle$ are induced by a probe laser, which couples $|W_m, g\rangle$ to $|W_{m'}, e\rangle$ in either the same well or in neighboring wells, with coupling strengths of the same order for realistic U_0 (see figures 1 and 2). A sequence of probe laser pulses on resonance or detuned by Δ_g then provides a powerful method of spatially separating and re-combining the atoms on the WS ladder.

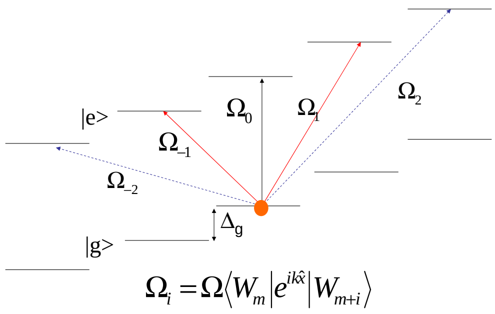

Fig. 1. Wannier-Stark ladder of states and couplings between states by the probe laser

Typically, about 10^3 to 10^4 atoms per lattice site can be trapped and cooled to a few μK, close to the reflecting mirror of the vertical trap laser. Once selected in a single vertical well (see below for details on how that is achieved), an interferometer is then created around that well using a sequence of probe laser pulses. Starting with atoms in state $|W_m, g\rangle$, a first $\pi/2$ pulse on resonance creates a superposition of $|W_m, g\rangle$ and $|W_m, e\rangle$. Next, a π pulse detuned by $+\Delta_g$ transfers atoms from $|W_m, g\rangle \rightarrow |W_{m+1}, e\rangle$ and $|W_m, e\rangle \rightarrow |W_{m-1}, g\rangle$ leaving a superposition of spatially separated states in wells $m+1$ and $m-1$. After a time T a "symmetrization" π pulse on resonance switches internal states. A time T later a π pulse detuned by $-\Delta_g$ transfers atoms back ($|W_{m+1}, g\rangle \rightarrow |W_m, e\rangle$ and $|W_{m-1}, e\rangle \rightarrow |W_m, g\rangle$) with a final $\pi/2$ pulse on resonance recombining the atoms in the initial well m, where the internal state is detected. The different energies of the states along the two paths and the initial phases of the probe laser pulses lead to an overall phase difference

$$\Delta\phi = \frac{1}{\hbar}\ (m_a g \lambda_l + U_{m+1} - U_{m-1})\, 2T + \left(\omega_{eg}^{(m+1)} - \omega_{eg}^{(m-1)}\right) T \\ -\phi_s^{(1)} + 2(\phi_s^{(2)} - \phi_s^{(3)} + \phi_s^{(4)}) - \phi_s^{(5)} \tag{1}$$

where $\omega_{eg}^{(m)}$ is the separation between internal states in well m, $\phi_s^{(i)}$ is the initial phase of the i th pulse of the probe laser and U_m an additional perturbation (QED, new interaction, stray e-m fields, etc...). The signal of interest allows the measurement of a potential U that varies over the size of the interferometer. Assuming state of the art measurement noise of atom interferometers, $\Delta\phi$ can be determined with a precision of $\approx 10^{-4}$ rad after 10^3 to 10^4 s integration. For interaction times $2T \approx 0.1$ s this corresponds to a measurement noise on $(m_a g \lambda_l + U_{m+1} - U_{m-1})/(2\pi\hbar)$ of about $1.6\ 10^{-4}$ Hz.

The experiment will be carried out with Rb atoms. Atomic states will be manipulated using two-photon Raman transitions. The momentum of the probe laser is then $k_{eff} = k_1 - k_2$, which corresponds to an effective wavelength of 390 nm. Efficient coupling between neighbouring wells is then expected to occur for $k_L \simeq k_{eff}$, which corresponds to a blue detuned trap for the lattice. In that case, $\Delta_g/2\pi$ is on the order of 500 Hz.

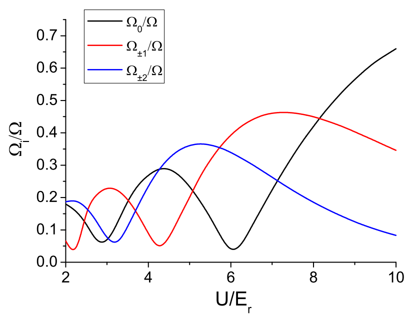

Fig. 2. Relative coupling strengths of the transitions in the same well and into the four first neighbouring wells ±1 and ±2 as a function of the lattice depth U_0.

An important feature of this experiment lies in the influence of the depth and wavelength of the lattice on the coupling strength for transitions between wells. Good couplings between adjacent wells can be realized with lattice depths on the order of a few recoil energies, and the ratio between same well - adjacent wells transitions can be adjusted at will by tuning the lattice depth and wavelength. We find a remarkable feature at 532 nm, for which high power single mode lasers exist. Figure 2 displays, for this specific lattice laser wavelength, the coupling strengths for transitions in the same well, between states in adjacent wells as well as between states separated by 2 wells.

The couplings are normalized by the coupling in the absence of the lattice. At $U \simeq 3$ Er (with Er the recoil Energy at the lattice wavelength), the coupling strength for a transition between adjacent wells is larger than for transition in the same well. If using copropagating Raman lasers, instead of counterpropagating lasers, the effective wavevector k_{eff} becomes negligible and only transitions in the same well are allowed (only $\Omega_0 \neq 0$). This suggests a strategy in addressing given transitions with very large efficiency by setting the lattice depth where one coupling strength is dominant (e.g. at

$U \simeq 3$ Er), and using depending on the transition required either counter or copropagating transitions.

With a lattice beam at 532 nm laser, an additional red detuned (progressive) beam for transverse confinement, which will be realized with an infrared laser, operating at 1030 nm. The choice of this wavelength is motivated by the possibility to additionally generate green light, at a wavelength of 515 nm, close to the lattice wavelength, by frequency doubling, which will be useful for well selection. Overlapping this second green vertical beam with the lattice beam results in a super-lattice, whose wells depth is modulated, with a characteristic period of 8 μm. This induces a position dependent resonance frequency for the transition between adjacent wells, which lifts the degeneracy between $m \to m+1$ transitions. Well selection is then achieved by applying a single Raman pulse which selectively transfers atoms from one of the wells to the adjacent well, and then clearing remaining atoms with a pusher beam.

3. Systematic effects

Many perturbations are expected to affect the measurement. We briefly detail some of the most important effects:

- Light shifts affect the measurement in two ways. First, a modification of the transition frequency ω_{eg} leads to imperfect cancelation of the second term in equation 2 if the lattice laser intensity varies in space and/or time. Second, a spatial variation of the intensity modifies the energy of the ground state $|g\rangle$, which leads to a contribution on the term $U_{m+1} - U_{m-1}$. Lattice depths of a few recoils correspond to several tens of kHz of light shift, which is 8 orders of magnitude larger than the target frequency shift accuracy. As the transition between hyperfine states is affected only by the differential shift, a reduction by 5 orders of magnitude of the first effect is expected with respect to the case where the two states would be coupled by an optical transition. Thus, a reasonable temporal and spatial stability of the laser intensity will be sufficient. As for the second effect, spatial intensity variations need to be controlled at the 10^{-8} level, which, whilst challenging, is still possible over the relatively short distances involved. For example, the results of Ref. 6 are consistent with $< 10^{-8}$ control of spatial intensity variations. Although controlling the intensity close to the surface is certainly more difficult, Ref. 6 provides a good indication that light shifts due to spatial intensity fluctuations should be controllable at the required level.

- The uncertainty of any measurement of atom-surface interactions depends crucially on the precise determination of the distance between the atom and the surface. Here, the precise knowledge of the position of the wells of the lattice with respect to the surface allows determining the atom-surface separation, which an accuracy limited by wave-fronts distortions. Over the small extension of the trapped atoms ($\approx 100\mu$m) it should be possible to control wave front flatness to about $10^{-3}\,\lambda_l$. However, interference between the trap laser and stray reflections due to surface roughness may play a non-negligible role. Other effects could come from surface roughness ($\approx 0.5\,$nm). Therefore, we expect to control the atom-surface separation to $\approx 1\,$nm.

- For Rb the main limitation identified in Ref. 5 is related to collisions between atoms and resulting differential energy shifts due to a density difference in the two wells of the superposition. We will solve that problem by using a powerful trapping laser that allows a large waist (1 mm) and correspondingly low densities whilst keeping a reasonable number of atoms. With 10^3 atoms per well the density will be of order 10^{10} at/cm^3 and the corresponding absolute shift is about 7×10^{-2} Hz. The differential density can be controlled at the 10^{-3} level by selecting atoms using adiabatic passage schemes, as developed for microwave clocks.[7]

- Finally, one of the most significant error sources in the measurement reported in Ref. 4 are stray electric and magnetic fields originating from contaminations of the surface. In our case this is likely to be less of a problem: the characterization of magnetic effects is likely to be more precise than in Ref. 4 because of the absence of a magnetic trap, as the different m_F states can then be used to measure the magnetic fields "in situ". Stray electric fields remain a challenge, which we will address by applying controlled external electric fields (similar to Ref. 4,8). In particular Ref. 8 has shown that very accurate characterization of electric fields is possible and that heating of the surface can significantly reduce such fields.

4. QED potential

A rough calculation of the QED potential for Rb atoms in the optical lattice is shown in Table 1, with the expected relative uncertainty of its measurement, taking into account the uncertainties on the determination of potential (10^{-4} Hz) and distance (10^{-9} m).

At short distances the uncertainty is dominated by the uncertainty of the distance determination, at large distances by the uncertainty of the potential measurement. The optimum is situated around 6 μm where the relative uncertainty is less than 10^{-3}, which is two orders of magnitude better than the best present atomic (ie. Casimir-Polder) measurements.

Table 1. QED potential for Rb in different wells of the optical lattice at 532 nm and at $T = 300$ K, and the expected relative uncertainty in its determination.

Well No.	1	2	5	22	50
r / nm	266	532	1330	5852	13300
U_{QED} / Hz	5×10^4	3131	80	0.34	0.03
$\delta U_{QED}/U_{QED}$	0.01	8×10^{-3}	3×10^{-3}	6×10^{-4}	3×10^{-3}

It is well into the region where theoretical calculations and predictions of the effect of quantum fluctuations need to take into account a number of parameters (surface properties, atomic polarizabilities, finite temperature). For example the optimum distance (~ 6 μm) is close to the crossover between the vacuum (r^{-4}) and thermally (r^{-3}) dominated regimes, situated around 4 μm at $T = 300$ K.

5. Test of gravitation

Considering the search for new interactions related to gravity, experiments set limits in the α, λ plane. Figure 3 (from Refs. 9,11) shows the present experimental exclusion regions in the 10^{-6} m to 10^{-3} m range, together with some theoretical predictions for new interactions (shaded colored regions) and the estimated limits attainable using our proposed experimental setup assuming a 10^{-4} Hz resolution, (green and purple line) with a sapphire surface (density ~ 3980 kg/m^3).

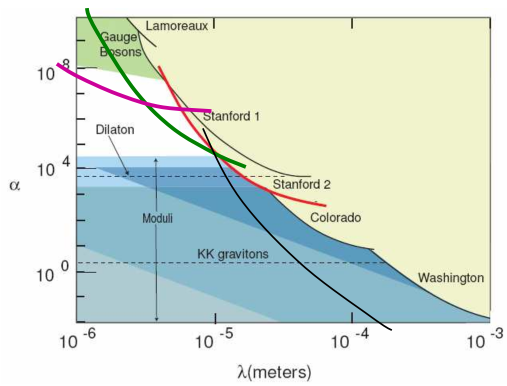

Fig. 3. Present limits on additional interactions related to gravity. The figure has been taken from Ref. 9. A black line was added to take into account more recent results obtained by the Washington group.[11] The green and purple lines show the estimated limits from FORCA-G in the first and second stage respectively (see text for details).

The most serious issue when trying to measure additional gravitational interactions is the perturbation from U_{QED}, especially at short distances. Table 1 shows that for measurements in the 3rd well one needs to correct and/or cancel the effect of U_{QED} at the 10^{-6} level for the 10^{-4} Hz uncertainty that we aim at, and even when relatively far from the surface (50th well) a correction at the % level is still required. We will address that issue in a two stage experiment, starting with an experiment at relatively large distance ($> 10\mu$m) where U_{QED} can be modeled and corrected to the 10^{-4} Hz level, and exploring shorter separations in a second stage where U_{QED} is canceled in a differential measurement between the two isotopes (^{85}Rb and ^{87}Rb), as U_{QED} is dependent on the atomic polarizability, which is the same for the two isotopes down to isotopic shifts ($\leq 10^{-6}$). The two colored lines in figure 3 show the estimated limits in the two stages. They correspond to improvements on present limits by more than three orders of magnitude in the 1 μm to 10 μm region. At shorter ranges, present limits are less well established (see e.g. the review[10]) but we expect similar improvements from our experiment down to about $\lambda \sim 100$ nm.

6. Conclusion

The proposed experiment will allow the measurement of U_{QED} (Casimir-Polder force) below the % level, well into the interesting region where refined theoretical predictions are required, and about two orders of magnitude below the best present measurements. Furthermore, it will allow setting new stringent limits on short range modifications of gravity, in the theoretically interesting range of 10^{-7} to 10^{-5} m and with up to three orders of magnitude improvement on present limits. The project therefore has a large potential for discoveries that may well lead to breakthroughs in our current understanding of physics and the universe at all scales.

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