COLD ATOM GRAVIMETER

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In this article some basic and widely used cooling and trapping techniques for obtaining cold atom gases are presented. Amongst those are optical molasses, evaporative cooling, and magneto-optical trap. The most important physical properties of cold atoms are stressed in an introduction to cold atom interferometry. The principles of cold atom gravity meter are explained to some extent. It has many benefits and better accuracy compared to classical gravimeters. Potential uses in geodesy, navigation, earth's gravity field mapping, as gravity wave detectors, and for testing fundamental gravitational laws and theories are also briefly discussed.

GRAVIMETER NA HLADNE ATOME

V članku je najprej predstavljenih nekaj najpogosteje uporabljenih metod za hlajenje atomov: optične molase, hlajenje z izhlapevanjem atomov in magneto-optično past. S kvantnimi lastnostmi hladnih atomov je razložena interferometrija hladnih atomov. To je glaven princip, ki omogoča zelo natančno merjenje pospeškov s hladnimi atomi. Poudarek je na merjenju gravitacijskega pospeška, saj ima tak instrument veliko prednosti pred klasičnim. Za konec so na kratko predstavljene možne uporabe gravimetrov na hladne atome v geodeziji, navigaciji, za mapiranje zemljinega gravitacijskega polja, kot detektorji gravitacijskih valov in za testiranje fundamentalnih zakonov gravitacije.

1 Introduction

Many experiments showed us that light carries momentum. We've learned from the wave-particle duality that light can be described by particles called photons and also that particles of matter have wave nature, especially when dealing with very small particles and cold environments. The latter was confirmed with numerous experiments, for instance Young's double slit experiment with electrons, atoms, even molecules. Current record holder for the largest thing for which this experiment has been performed is a molecule with 10000 atomic mass units.

Wave-particle duality is a basic assumption in quantum mechanics. The de Broglie wavelength of a particle at some finite temperature is $\lambda = \frac{h}{p} = \frac{h}{\sqrt{2\pi m k_\mathrm{B} T}}$, where h is the Planck constant, k_B is the Boltzmann constant, m is particle's mass, and T is its temperature. This wavelength is usually much smaller than the physical distance between two such particles, but when the two are comparable, quantum statistics for fermions and bosons, instead of the classic Boltzmann, must be considered. This determines whether quantum effects are important. Ultra cold atom gases are such systems. Ultra cold bosons undergo a state called Bose-Einstein condensation (BEC), which is among the most fascinating phenomena in nature.

In this article I will first explain some techniques of cooling and maintaining ultra cold atom gases. Next I will show that atom interferometry, which is only possible with cold coherent atoms, can be used to develop interesting and useful apparatuses: rotation sensors, cold atom gravimeters and gravity gradiometers. I will describe the last two. Both are better than conventional instruments in many ways, especially in their precision. This is due to much shorter de Broglie wavelength of the atoms compared to laser light used in interferometers in conventional gravimeters. This will greatly improve instruments in navigation, geodesy, and oil and mineral exploration. Very precise gravity measuring may also lead to new discoveries in fundamental theories of gravity. In the end I will briefly present a gravity wave detector that works on a very similar principle.

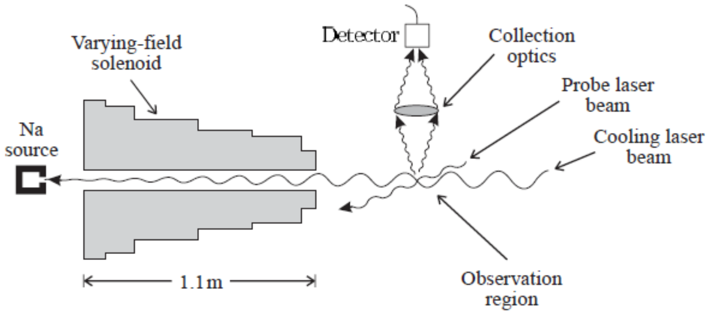

Figure 1. A scheme of the first Zeeman slowing experiment. A probe laser beam intersecting the slow atomic beam gives a fluorescent signal proportional to velocity distribution. Adapted from [1].

2 Laser trapping and cooling

2.1 Slowing an atomic beam

Light can be described using photons with well defined momentum:

$$p_{\mathrm{ph}} = \frac{E}{c} = \frac{\hbar\omega}{c} = \frac{h}{\lambda}\,, \tag{1}$$

where $\hbar$ is the reduced Planck constant, c is the speed of light, E is photon's energy, ω is its frequency and λ its wavelength. When an atom absorbs a photon total momentum must be conserved, so the atom of mass m feels a slight "kick" of recoil velocity $v_{\mathrm{r}}^{\mathrm{i}} = \frac{p_{\mathrm{ph}}}{m}$ in the direction of the incoming photon. When the atom spontaneously decays back to ground state, another photon of the same wavelength is emitted in random direction. In the limit of a large number of such events the recoil velocity of emitted photons averages to $\langle v_{\mathrm{r}}^{\mathrm{e}} \rangle = 0$ [1].

The same principle applies when slowing or accelerating an atomic beam with a laser. Laser produces a collimated monochromatic beam of light, which means a large number of photons with equal energy $E = \hbar\omega$. If this energy matches a transition between two energy states of the atom $\Delta E = \hbar\omega_0$, where ω_0 is the transition frequency, cross section for absorbtion $\sigma_{\mathrm{abs}}(\omega = \omega_0)$ of such a photon greatly increases. Under this resonance condition, a large number of incoming photons are absorbed and net force on the atoms is considerably big. It depends mainly on the number of photons in the laser beam, which is basically the intensity of the laser beam I, and the detuning from the atomic resonance $\delta = \omega_0 - \omega$, which is contained in the absorption cross section. The scattering force is:

$$F_{\mathrm{scat}} = -\sigma_{\mathrm{abs}} \frac{I}{c}\,. \tag{2}$$

2.2 Zeeman slower

In an actual application of this principle to decelerate an atomic beam, one has to take into account the Doppler shift of laser beam in atoms' moving frame. Spectrum of laser light is a Gaussian shaped peak, with mean frequency ω, and small, but finite, spectral width. This width is still small compared to the Doppler shift when atoms decelerate from the initial thermal velocity of atoms, when they exit the oven at about $v_{\mathrm{i}} \sim 1000\,\frac{\mathrm{m}}{\mathrm{s}}$, $T_{\mathrm{i}} \sim 1000\,\mathrm{K}$, to final velocity and corresponding temperature of the order of $v_{\mathrm{f}} \sim 0.1\,\frac{\mathrm{m}}{\mathrm{s}}$, $T_{\mathrm{f}} \sim 100\,\mu\mathrm{K}$. The Doppler shift for velocities v, much smaller than the speed of light $v \ll c_0$, is:

$$\Delta\omega = \frac{v}{c}\omega = kv\,, \tag{3}$$

where k is the size of the wave vector of laser light. To stay in resonance with laser light,[1] one must change the atom transition frequency as they slow down. One way of doing exactly that is by using a *Zeeman slower*. It is based on the Zeeman effect. The change in transition frequency depends on magnetic quantum number of initial and final hyperfine atom states M_i, M_f, the corresponding Landé g-factors g_i, g_f, and magnetic field B: $\hbar\Delta\omega_0 = (g_\mathrm{f}M_\mathrm{f} - g_\mathrm{i}M_\mathrm{i})\mu_\mathrm{B}B$. Optical transitions usually occur between atom states with $\Delta M = M_\mathrm{f} - M_\mathrm{i} = 1$. For the sake of convenience, one can say $\Delta\omega_0 = \frac{\mu_\mathrm{B}}{\hbar}B$, which is off by a constant factor at most. Adding the Zeeman frequency shift, the resonance condition is:

$$\omega_0 + \frac{\mu_\mathrm{B}}{\hbar}B(z) = \omega + kv(z)\,, \tag{4}$$

where $B(z)$ is a spatially varying magnetic field that changes appropriately with the change of velocity $v(z)$. Technically, Zeeman slower in Fig. 1 is a system of magnetic coils, all wrapped around the same axis. These coils generate the correct profile of magnetic field $B(z)$, parallel to laser beam, to compensate for the Doppler shift during deceleration.

The important feature of this slowing technique is that it works well for a large fraction of atoms coming out of the oven. All atoms with initial velocities lower or equal to v_max will satisfy the resonance condition (4) at some point along the Zeeman slower and decelerate thereafter. This way most of the atoms can be efficiently decelerated in one dimension from initial velocity of a few $100\,\frac{\mathrm{m}}{\mathrm{s}}$ down to about $v \approx 0\,\frac{\mathrm{m}}{\mathrm{s}}$ in less than $1\,\mathrm{m}$ of length, with corresponding maximum magnetic field of about $B = 0.1\,\mathrm{T}$, which is easily obtainable [1].

2.3 Optical molasses

Zeeman slower efficiently decelerates and cools atoms in one direction, but a different apparatus is necessary to keep the gas of atoms bunched together and reduce their temperature further in all directions. Optical molasses consist of three pairs of laser beams, one for each orthogonal axes. All lasers have the same frequency and are slightly red-detuned – their peak frequency is slightly above transition frequency. The symmetrical arrangement of lasers exerts equal and opposite forces on stationary atoms and therefore has no net effect. However, if an atom is moving in laboratory frame towards one of the lasers, its frequency is Doppler shifted so that it matches better to the atom's resonance, therefore its force on the atom increases and vice versa for the opposite laser (as in Fig. 2). Net force on the atoms in optical molasses is slowing the atoms, just like a moving object is damped in viscous fluid. For small velocities compared to laser spectral width $kv << \Delta\omega$, this force is given by:

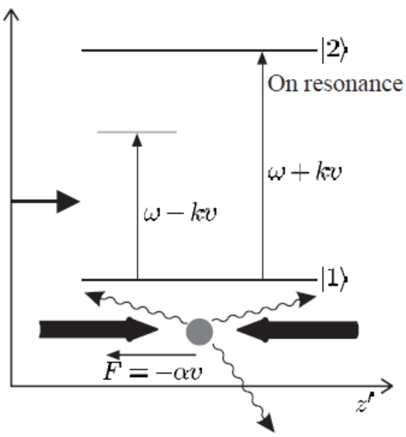

Figure 2. The atom's velocity in z direction Doppler shifts laser light. Consequently, non zero net force is exerted on the atoms. Adapted from [1].

$$F = -\alpha v\,, \tag{5}$$

where α is the effective damping coefficient.

Using a beam splitter to get two laser beams for each orthogonal direction, laser operation noise can be eliminated, but even than one cannot use only this method to cool the atoms to less then $1\,\mathrm{nK}$, which is necessary for some experiments. The lower Doppler limit is about $T = 240\,\mu\mathrm{K}$ and mean velocity $v \approx 0.5\,\frac{\mathrm{m}}{\mathrm{s}}$ for sodium and about $T = 125\,\mu\mathrm{K}$ and $v \approx 0.1\,\frac{\mathrm{m}}{\mathrm{s}}$ for caesium [1]. The reason is in spontaneous emission and a corresponding random kick of velocity following each

[1] Laser frequency in laboratory system is constant.

absorbed photon. The lowest temperature limit is lower for heavier caesium, because the same random kick of photon's momentum changes heavier atom's velocity far less.

2.4 Magneto-optical trap

Another problem with the optical molasses is that the atoms slowly diffuse out of the trap, because they do not feel any position dependant force, pushing them back to the intersection of the orthogonal beams. The same configuration can be turned into a trap by correctly choosing opposite laser beams' polarisation and adding magnetic field gradient. Appropriate quadrupole magnetic field is achieved by two identical coils with opposite currents, one on each side of the trap, as shown on Fig. 3. If these are positioned just right, the magnetic field in the central point of optical molasses is 0 and $|\mathbf{B}(\mathbf{r})|$ increases in every direction. Magnetic field does not confine atoms by itself, but it causes an asymmetry in the opposite lasers' scattering forces, which strongly confines the atoms.

We will illustrate the principle of trapping on a simple $J = 0$ to $J = 1$ transition shown in Fig. 4, where J is the total angular momentum of the atom. Around the point of zero magnetic field $B = 0$, there is a uniform field gradient. Let's first consider z direction in Fig. 3: $B \approx \gamma z$. Magnetic field perturbs atomic energy levels with equal energy in zero field $J = 1$; $M_J = -1, 0, +1$; to three different energy values: $E_{J,M_J} = g\mu_\mathrm{B} M_J B = g\mu_\mathrm{B} M_J \gamma z$. At $z = 0$ all transitions are equally possible, so net force is 0. However, at $z > 0$ state with magnetic quantum number $M_J = -1$ has lower energy and is therefore more likely. Red detuning causes increased absorption to this state $M_J = -1$, with slightly lower transition frequency $\delta\omega = -g\frac{\mu_\mathrm{B}\gamma}{\hbar}z$. What is more important, laser light coming from the positive direction has negative circular polarization with angular momentum $\sigma^- = -\hbar$ and is therefore allowed for the transition $J = 0$, $M_J = 0$ to $J = 1$, $M_J = -1$, while the opposite laser beam has positive circular polarization $\sigma^+ = +\hbar$ and absorption is only allowed through a less likely (more detuned) transition to $J = 1$, $M_J = +1$. Hence, net force pushes the atoms back towards the intersection point $z = 0$. The same consideration is done for $z < 0$: $\mathbf{B}$ has the opposite direction, and the most probable state, with lowest energy, becomes $M_J = +1$. In the end, force is given by:

$$\mathbf{F} = -\alpha\mathbf{v} - \frac{\alpha\gamma}{k}\mathbf{r}\,, \tag{6}$$

where all three orthogonal directions are already considered. In this equation, the first term is the damping force from equation (5) and the second is a restoring force with effective spring coefficient $\frac{\alpha\gamma}{k}$ for small deviations z; k is length of wave vector of light.

The result is an over-damped oscillator, which is widely used for collecting and cooling atoms before further experiments. It is easy to load with a Zeeman-slower and can hold great amounts of gaseous cold atoms $N \sim 10^{10}$ at high densities. The lowest temperatures reached in magneto-optical traps (MOT) are higher than in optical molasses. For further cooling, other mechanisms are required.

2.5 Further cooling techniques, BEC

We will not go in details of other cooling techniques. With optical molasses and MOTs, the theoretical Doppler limit was predicted to be about $T = 125\,\mu$K. However, even colder temperatures are experimentally observed. That is because of a phenomena called *Sisyphus cooling technique*, which has to do with the interaction of an atom with the standing electromagnetic wave – the laser field. It turns out that the actual limit for optical molasses is about $T_\mathrm{c} \sim 1\,\mu$K. This corresponds to a few photons' recoil velocity, which is about $v_\mathrm{r} \sim 1\,\frac{\mathrm{cm}}{\mathrm{s}}$ for caesium atoms [3].

However, certain experiment require even lower temperatures. To reach Bose-Einstein condensation, one must cool the alkali atoms to about $T_\mathrm{c} \sim 0.1\,\mu$K or even lower [2]. Many fascinating

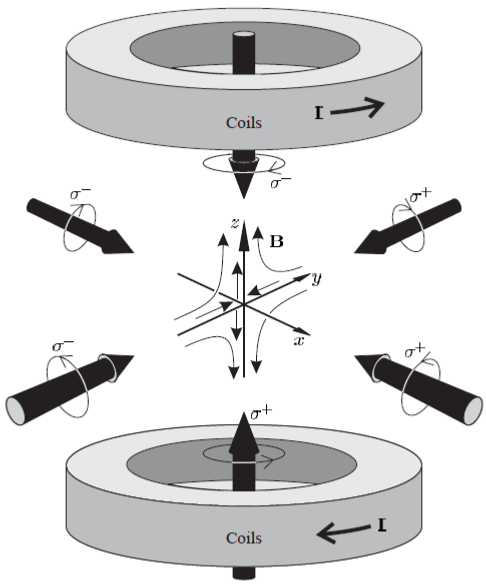

Figure 3. A scheme of magneto-optical trap with 3 pairs of laser beams and 2 magnetic coils that produce quadrupole magnetic field, shown on the graph. Adapted from [1].

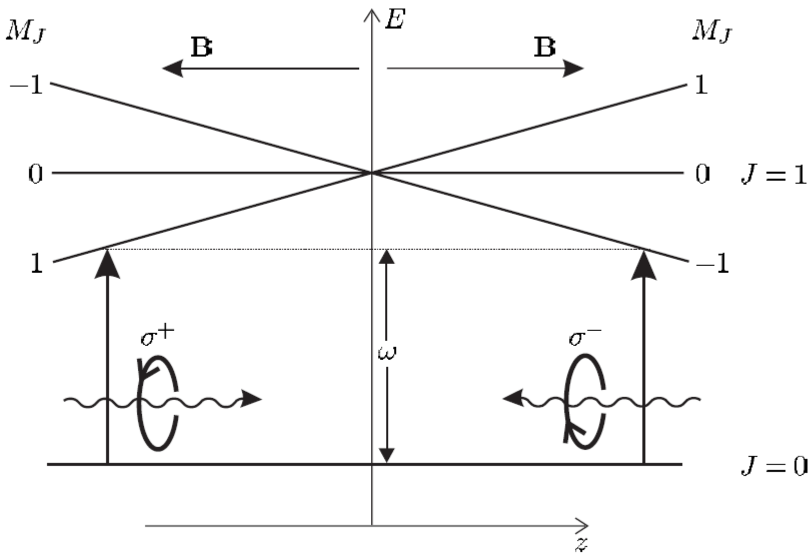

Figure 4. The most probable transitions for a slightly red-detuned laser frequency in different magnetic field above or below trapping point. A scheme of two opposite laser beams, with correct circular polarizations, corresponding to selection rules for transition. Adapted from [1].

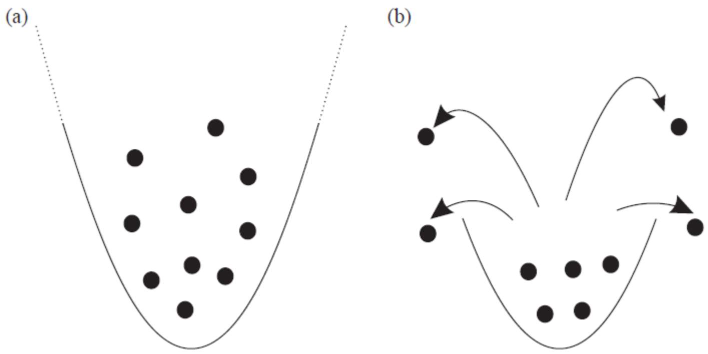

Figure 5. Schematic presentation of evaporative cooling. Atoms in a harmonic potential trap have some kinetic energy distribution (a). By lowering the trapping potential, the fastest atoms with the highest energy escape (b). Adapted from [1].

phenomena that derive from quantum mechanic nature of bosons have already been experimentally observed in such systems. There are numerous theoretical predictions, that show quantum nature of BEC, some still to be experimentally observed, and many potential uses for such systems in atomic clocks, precision measurement, quantum computing... To reach BEC, one must satisfy this equation for critical temperature [2]:

$$T_\mathrm{c} = \frac{2\pi\hbar^2}{k_\mathrm{B}m}\left(\frac{n}{2.612}\right)^{2/3}, \tag{7}$$

where n is the number density of the atoms in BEC.

Next stage of cooling is possible with another method called *evaporative cooling*. The principle is that the fastest atoms with the highest kinetic energy are left to escape the trap by lowering the trapping potential (shown in Fig. 5), that is turning the trapping laser intensity down. If only the fastest atoms are let loose, they carry away more than average kinetic energy, therefore the average kinetic energy of the remaining atoms decreases. This way the cloud of atoms is gradually cooled to temperatures of the order of $T \sim 1\,\mathrm{nK}$ or even less, low enough for quantum wave functions of bosons to start overlapping. De Broglie wavelength $\lambda_\mathrm{B} = \frac{h}{p}$ is considerably long, compared to the distance between atoms, and this means that quantum effects become crucial. Strong correlations between particles give rise to strong coherence and bosons start condensing into a single ground state, so they can all be attributed a single macroscopic wave function [2].

The only limit of evaporative cooling is decreasing the number density of atoms so much, that BEC is no longer possible in accordance with equation (7).

In 2007, interference between two Bose-Einstein condensates was observed experimentally [2]. Two condensates, separated by $d = 40\,\mu\mathrm{m}$ were prepared in a double well potential. After it had been turned off, the gas was left to expand freely and interference fringes with wavelength $\lambda = \lambda_\mathrm{B} = \frac{ht}{md}$ were observed after time $t = 40\,\mathrm{ms}$. This demonstrates the coherence and long-range correlations in BEC, which are properties of a laser. In this sense an atom laser with coherent matter waves can be constructed.

3 Gravimeter

A common state-of-the-art gravity meter based on light interferometry is the falling corner cube gravimeter, shown in Fig. 6 [4]. It is basically a Mach-Zehnder interferometer: the main parts are the beam splitters, that coherently split the input laser beam to test beam and reference beam, and the two corner cube mirrors. The upper one is a free falling test mass in ultra high vacuum and the lower one is a stationary corner cube in an inertial frame of reference. The test beam bounces off the falling corner cube, then off the lower stationary corner cube and is then guided back to overlap with the reference beam, which travels straight through the interferometer. Interference fringes are then recorded to track the free falling test mass. Gravitational acceleration is derived from interference data. For precision measuring this 3 second procedure is repeated about 100 times.

Cold atom gravimeter is in principle also a Mach-Zehnder interferometer, but with matter waves instead of laser light. The test masses are cold atoms in gas phase and beam splitting and mirror reflection is achieved with a proper Raman laser light pulse. We will discuss its basic principles in the next few sections. This interferometer gives much better stability to seismic and other vibrational noise. Because it has no movable mechanic parts, it is also more convenient for use on a boat or on a plane. Compact cold atom gravimeters with the same capabilities as classical portable gravimeters for field applications have already been developed [6].

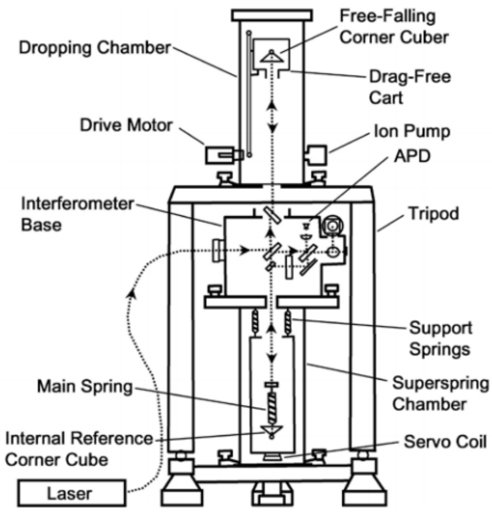

Figure 6. FG5 falling corner cube gravimeter. Adapted from [5].

After 86 s, precision for falling corner cube gravimeter is at $10^{-8}\,\frac{\mathrm{m}}{\mathrm{s}^2}$, while the cold atom gravimeter gets to the same precision after only 32 s [7]. It achieves much higher repetition rates and faster measuring times. Measurements in geophysics that have $5 \cdot 10^{-}9\,\frac{\mathrm{m}}{\mathrm{s}^2}$ precision take about 15 minutes with current sensors but take less than 1 minute using state-of-the-art cold atom gravimeters.

Many different configurations and different atoms were proposed for this purpose. In this article I will describe Caesium atoms in an atomic fountain. Caesium is one of the heaviest bosons, which means it's easier to cool than lighter elements and even Bose Einstein condensate is in reach. It's hyperfine ground state is $6s_{1/2}$, $F = 3$, $M_F = 0$, with a microwave transition to $6s_{1/2}$, $F = 4$, $M_F = 0$ and optical transitions to $6p_{3/2}$, $F' = 4$ or $F' = 5$.

3.1 Stimulated Raman transition

Stimulated Raman transition is a two photon process [9],[3]. An atom is illuminated from opposite sides with two lasers, whose frequency difference ω_{eff} is equal to the frequency of transition between atom hyperfine energy levels $F = 3$ and $F = 4$. Let's say that laser light coming from below has higher frequency ω_1 and the one from above $\omega_2 = \omega_1 - \omega_{\text{eff}}$, corresponding to the wavevectors in Fig. 7. Both light beams are nearly resonant with an allowed optical transition to a higher state $|i\rangle$, but far enough detuned from $\omega_j = \omega_{j\to i} - \Delta$, that the spontaneous emission rate from that level is negligible. Under this condition, the only allowed coupling with the incoming laser light is by a two photon Raman transition, when the atom absorbs an incoming photon from below ω_1 and emits another photon with ω_2 by stimulated emission in the opposite direction. During this Raman transition the atom changes state and simultaneously receives a momentum kick $\hbar\mathbf{k}_{\text{eff}}$, corresponding to the vector sum of momentum of the two photons with opposite directions of travel: $\mathbf{k}_{\text{eff}} = \mathbf{k}_1 - \mathbf{k}_2$.

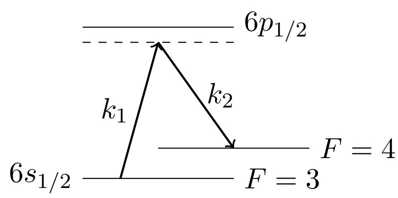

Figure 7. Caesium hyperfine levels used in Raman transition. Wave vectors of the two opposite laser beams are k_1 and k_2.

Detailed analysis of this 3 level quantum system, illuminated by a Raman beam, derived in [9] and [10] leads to Rabi flopping between the two $F = 3$ and $F = 4$ levels with an effective Rabi frequency Ω_{eff}. The latter also depends on the initial phase of the laser fields, which will lead to atom's sensitivity to inertial forces.

By choosing the correct length of the Raman laser pulse, beam splitters and mirrors are realized. When the pulse length τ is exactly $\tau\Omega_{\text{eff}} = \pi$, all atoms change state and receive a photon recoil kick, and when the pulse length is $\tau\Omega_{\text{eff}} = \frac{\pi}{2}$, an equal superposition of both states is created, while only the excited states feel the recoil kick – this is a beam splitter that spatially separates the superposition of $F = 3$ and $F = 4$ states. These are called π pulses, and $\frac{\pi}{2}$ pulses, respectively, as in nuclear magnetic resonance.

3.2 Atomic Fountain

At the beginning of the experiment we prepare a bunch of atoms in the ground state with a narrow 1D velocity distribution.

Caesium atoms are heated to about $90\,^{\circ}\mathrm{C}$ to evaporate and then loaded to a magneto-optical trap with a Zeeman slower. When sufficient amount of atoms $N \sim 10^9$ are bunched together, magnetic field is turned off and atoms are cooled further by optical molasses technique so they reach $T \sim 2.5\,\mu\mathrm{K}$ [3]. Then an atomic fountain is formed by detuning the top lasers and increasing the frequency of the bottom lasers by the same amount. This way the atoms reach equilibrium velocity of about $3\,\frac{\mathrm{m}}{\mathrm{s}}$ in vertical direction. This way the atoms travel about 1 m. The optical molasses lasers intensity is also turned down for evaporative cooling. A laser pumping beam pumps most of the atoms to the $F = 4$ state. A Raman transition π laser pulse induces transition for most of the atoms to the $F = 3$ state, followed by a short intense laser pulse in resonance with the optical transition $F = 4 \rightarrow F' = 5$ blasts away the remaining atoms. Another velocity selective Raman π pulse then transfers atoms back to $F = 4$ state, followed by another optical pulse in resonance with transition $F = 3 \rightarrow F' = 2$, which pushes the remaining atoms away. After some of these velocity and state selective pulses only about 1% of the atoms are left, but their vertical velocity distribution is much narrower, corresponding to a 1-D temperature of $T \sim 1nK$. This narrow velocity distribution is required in interferometry for coherence and good fringe contrast. Bose-Einstein condensates would probably give the best results, but are a little tricky to reach and also even larger fraction of atoms are lost in the process of cooling.

3.3 Mach-Zehnder interferometer

Mach-Zehnder interferometer is realized with a sequence of Raman pulses $\frac{\pi}{2}$, π, $\frac{\pi}{2}$ in vertical geometry in an atomic fountain. T in Fig. 8 is time between two pulses. At $t = 0$ the first $\frac{\pi}{2}$ pulse creates a coherent superposition of states $|3, \mathbf{p}\rangle$ and $|4, \mathbf{p} + \hbar\mathbf{k}_{eff}\rangle$ denoted $|a\rangle$ and $|b\rangle$ in the Fig. 8. After time T, when atoms are the furthest apart, a π pulse redirects each wave packet by inducing transitions $|4, \mathbf{p} + \hbar\mathbf{k}_{eff}\rangle \rightarrow |3, \mathbf{p}\rangle$ and $|3, \mathbf{p}\rangle \rightarrow |4, \mathbf{p} + \hbar\mathbf{k}_{eff}\rangle$. After another time interval T the wave packets again overlap and another $\frac{\pi}{2}$ pulse causes them to interfere.

From the Schrödinger equation one can derive that each time the state of the atoms changes during such an interaction, quantum atom states acquire additional *phase shift* from the Raman pulse [10]. This phase shift depends on the atom vertical position z_i at the time of interaction [3]: $\Phi_{\mathrm{i}} = k_{\text{eff}} z_{\mathrm{i}} - \omega_{\text{eff}} t_{\mathrm{i}}$. This phase actually locates atomic wave packets with respect to the reference frame, defined by the optical field. Total interferometer phase shift, corresponding to the notation in Fig. 8, is $\Delta\Phi = (\Phi_1^{\mathrm{A}} - \Phi_2^{\mathrm{A}}) - (\Phi_2^{\mathrm{B}} - \Phi_3^{\mathrm{A}})$. Without a gravitational field the wave packets' trajectories are straight lines in $z(t)$ and the phase shifts cancel $\Delta\Phi = 0$. Introducing acceleration $\mathbf{a}$, the trajectories change and the total phase shift can be derived by classical computation of all phase shifts Φ_i:

$$\Delta\Phi = \mathbf{k}_{\text{eff}}\mathbf{a}T^2\,, \tag{8}$$

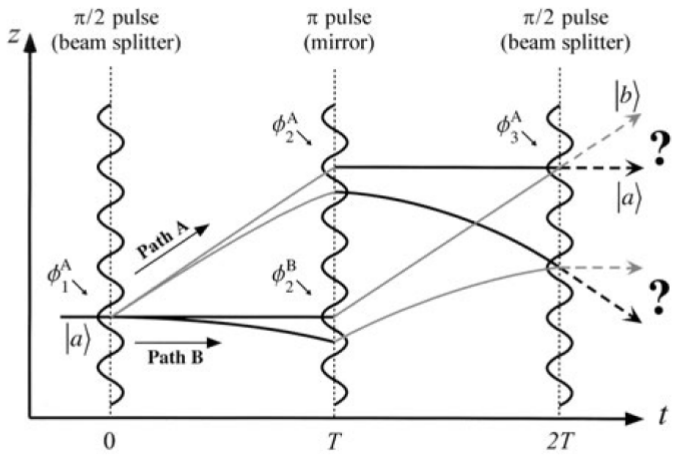

Figure 8. Mach-Zehnder atom interferometer with and without gravity. Dark lines represent hyperfine level $F = 3$ and light lines $F = 4$. Adapted from [3].

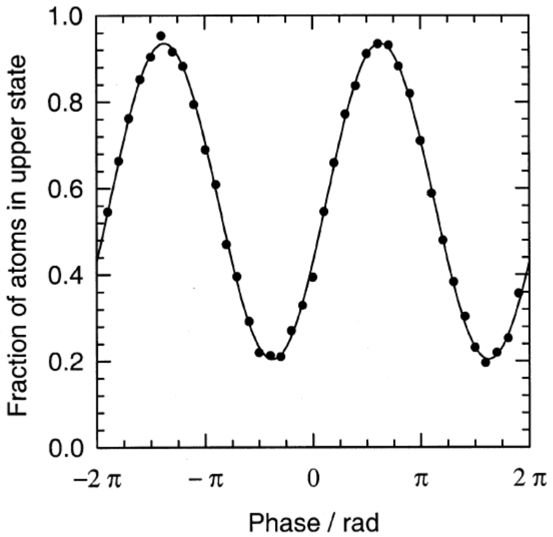

Figure 9. Typical fringes measured with a cold atom gravimeter. The total phase $\Delta\Phi$ is varied by changing phase of the middle π pulse. A sine function is fitted to the data. Adapted from [3].

where the acceleration $\mathbf{a} = \mathbf{g} + \mathbf{a}_{\text{noise}}$ is a vector sum of gravitational acceleration $\mathbf{g}$ and other contributions, mainly the acceleration of the non-inertial reference frame. This phase shift is related to the probability of finding the atom at the interferometer output in the excited state $F = 4$ [10]:

$$P(F = 4) = \langle 4, \mathbf{p} + \hbar\mathbf{k}_{\text{eff}} | 4, \mathbf{p} + \hbar\mathbf{k}_{\text{eff}} \rangle = \frac{1}{2} \left[1 - \cos\left(\Delta\Phi + \Delta\Phi_{\text{noise}}\right)\right] . \tag{9}$$

3.4 Measuring gravity and extracting noise

The interferometer phase shift is derived from the measurement of fraction of atoms in the excited states $|F = 4\rangle$ via laser induced fluorescence. A probe laser with frequency matching the transition $6s_{1/2}$, $F = 4 \to 6p_{3/2}$, $F = 5$ illuminates the sample and induces fluorescence only in excited states, which is then quantitatively measured with a photomultiplier tube. Afterwards, another laser excites all the ground state atoms $6s_{1/2}$, $F = 3 \to 6p_{3/2}$, $F = 4 \to 6s_{1/2}$, $F = 4$ and, right after that, the probe laser illuminates the sample again for the same time period, this time measuring the number of all atoms.

A graph of interferometer fringes is in Fig. 9. Each point corresponds to one measurement. The total phase shift is varied by changing phase of the middle π Raman pulse. Acquiring this data and fitting it with a sine function gives us a resolution of about $10^{-8}\,\frac{\mathrm{m}}{\mathrm{s}^2}$ [3].

The phase shift in equation (9) includes a term $\Delta\Phi_{\mathrm{noise}}$ which has many different contributions. One important correction from the simplified version is adjusting the Raman laser beam frequency for each pulse to compensate for the Doppler shift in the atoms' non-inertial moving frame, accelerating in earth's gravity. Because the Raman beam phase is crucial for the measurement accuracy, the frequency must be adjusted with a well executed phase-continuous sweep $\omega = \omega_0 + \beta\,\delta t$, locked to a stable reference oscillator. Modern digital frequency synthesis techniques can produce such signals with enough accuracy. It turns out that by choosing parameter β just right, the total interferometer phase shift goes to $\Delta\Phi = 0$. This way the interferometer's accuracy is very good and the coefficient β can be actively changed and also gives us absolute value of g. Accuracy is limited by the effect of Coriolis force on the atomic beam. It turns out that this contribution to the net phase shift can be neglected if the atoms have very small horizontal velocity. Other technicalities are also important but will not be further discussed here [3].

Further calculations that take into account more atom states, to which optical transition might be possible, can improve accuracy. The effect of Coriolis force on the free falling atoms, gravity gradients, and many other contributions are considered for very accurate measurements. In a recent comparison with the falling corner cube gravimeter, the cold atom gravimeter showed better stability at about $0.2 \cdot 10^{-9}\,\frac{\mathrm{m}}{\mathrm{s}^2}$ and reaches accuracy to $10^{-9}\,\frac{\mathrm{m}}{\mathrm{s}^2}$ in 36 s compared to 86 s.

Equation (8) also indicates that longer interrogation time T increases sensitivity. Its upper value is limited by outside vibrations and thermal expansion of the cloud of atoms. In first experiments it was about $T = 50\,\mathrm{ms}$ and was raised to more than $T = 300\,\mathrm{ms}$ by active vibration isolation techniques for the best sensitivity [7]. Another problem is actually the physical size of the apparatus. Because atoms are measured during free flight, one would need a very long vacuum tube for a longer time of flight T. The obvious solution for very precise measurements for fundamental theories or earth's gravity field mapping is going to space. In microgravity conditions there is little external forces on the atoms, so time of flight is not limited by the size of the vacuum tube, but only by thermal expansion of the cloud. With ultra-low temperatures interrogation times can be as long as $T = 5\,\mathrm{s}$, so sensitivity increases greatly.

Magnetic and electric fields can also interact with the apparatus and mess up the results, so heavy metal magnetic shields are applied around the atomic fountain. Some other random vibrations can also be neglected using a nearby seismometer to correct the results after the measurement. This way one can subtract accelerations of the reference frame to get the real gravitational acceleration.

Another way of getting rid of platform noise is by using two gravity meters and measuring gradients instead.

3.5 Gravity gradiometer

Gravity gradiometer is just a system of two gravimeters on a common platform, spatially separated for a few meters. The two also share the same Raman laser which, ideally, propagates undisturbed between them. Therefore, any noise in Raman lasers is common in both systems. Since they share the same reference frame, common mode platform noise for a differential acceleration measurement is highly suppressed. This systems exist both in vertical configuration, which we already talked about, and horizontal, where the only difference is that the Raman pulse kicks are in horizontal direction. This way, vertical and horizontal gravity gradients are measured [11].

By neatly stacking a pile of bricks between the two gravimeters, a team of scientists managed to measure gravitational acceleration g with a resolution of $2 \cdot 10^{-8}\,\frac{\mathrm{m}}{\mathrm{s}^2}$ [11]. A measurement of gravitational constant G already almost matched the current record for a statistical uncertainty $1.2 \cdot 10^{-4}$. A precision of 10^{-6} is forecast for an improved version of their apparatus. A test for the Newton's gravitational force inverse square law was also done by gradually and accurately changing position of the test mass.

Other possible tests include testing the equivalence principle and some other general relativity stuff.

3.6 Gravitational wave detector

Terrestrial and space-based *gravity wave detectors* were proposed by Dimopoulus group [13]. Both are made of two widely separated atom Mach-Zehnder interferometers, coupled by three equally separated Raman laser pulses. These detectors use free falling atoms as test masses instead of mirrors as in LIGO. Seismic noise does not effect the falling atoms and that is why these detectors have better strain sensitivity than LIGO for low frequency signals. Lower frequency detectors are good also because they can detect gravitational waves from more common solar mass binaries megaparsecs away.

Figure 10. A in-laboratory gravity gradiometer working prototype by Jet Propulsion Laboratory, NASA. Adapted from [12].

LIGO just showed some results in 2015 when it detected gravitational waves from two black holes merging. When bigger objects like these merge, the last part of the merging happens really fast and produces high frequency signal that LIGO measured. The previous part of the merging produces lower frequency waves and lasts much longer. Smaller stellar objects like white dwarf binaries also produce lower frequencies and are much more common in the universe. Therefore, such events are predicted to be measured more frequently.

When a gravitational wave passes by, it causes an expansion of space between the two interferometers. Consequently, the phase of the Raman laser pulse is delayed on the way to the other interferometer, which produces a differential phase shift that can be measured.

Sensitivities of such sensors are predicted to be better than LIGO and LISA[2] on the frequency interval of about $10^{-3} - 10^{0}$ Hz at least for the space-based versions.

4 Conclusion

Cold Atom Laboratory is scheduled to launch to space in June 2017 and dock on the International Space Station [12]. Ultra-cold quantum gases in microgravity environment will be studied in this space-borne laboratory. Force free environment will enable interaction times as long as 20 s and temperatures as low as 1 pK. In such conditions different methods of cooling will be tested on different test atoms and new quantum phenomena might be observed. Atom interferometry experiments will also be executed. Hence, we see that all of this talk about going into space is not as far-fetched as one could imagine. Some of the experiments proposed in this article might possibly be carried out in NASA's Cold Atom Laboratory.

A super-precise gravity gradiometer for earth's gravity field mapping from space is still being improved and different geometries are being considered [8]. Such high sensitivity device in microgravity would be ideal for testing fundamental theories. One example of a different geometry is the

[2]LISA is another planned space-based programme for lower frequency gravity wave detection.

horizontal configuration, where gravitational constant G has already been measured to a statistical uncertainty of $3 \cdot 10^{-4}$, competitive to the current limit $1.2 \cdot 10^{-4}$ [11]. Some improvements are already being considered and uncertainties well bellow 10^{-5} are predicted. Other experiments aim to test Einstein's equivalence principle and test other fundamental laws of gravity. Many of these experiments help us improve our knowledge and understanding of the gravitational force. It is still not fully understood and yet to be somehow included in the standard model.

On the other hand, a terrestrial, compact, portable cold atom gravity gradiometer would be very useful for many technological applications, including geodesy, navigation, oil and mineral exploration [11]. Stationary laboratory gradiometers already exist and their sensitivity to gravitational acceleration or gravitational gradient already matches sensitivities of other gradiometers and is constantly improving with new studies.

Portable cold atom absolute gravimeters for field applications were already made in 2012. The main sensor with all the optics and electoronics fit in one $0.6 \times 0.7 \times 1.9\,\mathrm{m}$ rack [6]. Even smaller are being made, but with lower accuracy. They showed to be reliable and robust enough to work in a moving vehicle. Laboratory instruments have also been tested against state-of-the-art falling corner cube gravimeters and showed better results and faster measurement [7]. The reason is better isolation from seismic and other vibrational noise.

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