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Interaction of frequency modulated light pulses with rubidium atoms in a magneto-optical trap

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Abstract. The spatial displacement of the ^{85}Rb atoms in a Magneto-Optical Trap (MOT) under the influence of series of frequency modulated light pulse pairs propagating opposite to each other is measured as a function of the time elapsed after the start of the pulse train, and compared with the results of simulations. Adiabatic excitation and consecutive de-excitation take place between the ground $5\,^2S_{1/2}$ ($F = 3$) and the $5\,^2P_{3/2}$ ($F' = 2, 3, 4$) excited levels as the result of the interaction. The displacement of the ^{85}Rb atoms is calculated as the solution of simple equation of motion where the expelling force is that arising from the action of the frequency modulated light pulses. The restoring and friction forces of the MOT are taken into account also. The system of Bloch equations for the density matrix elements is solved numerically for transitions between six working hyperfine levels of the atom interacting with the sequence of the frequency modulated laser pulses. According to these simulations, the momentum transferred by one pulse pair is always smaller than the expected $2\hbar k$, (1) where $\hbar$ is the Plank constant and $k = 2\pi/\lambda$ where λ is the wavelength, (2) having a maximum value in a restricted region of variation of the laser pulse peak intensity and the chirp.

PACS. 32.80.Lg Mechanical effects of light on atoms, molecules, and ions – 32.80.Pj Optical cooling of atoms; trapping

1 Introduction

Intensive atomic beam of narrow velocity distribution and, at the same time, with well-defined slow velocity is often a requirement in experiments of high precision, for instance, in atomic fountain clocks [1] or transporting atoms between Magneto-Optical Traps (MOT-s) [2–4] or performing high precision measurements with cold atoms i.e. with atoms of small velocity spread [5].

In many papers the slowness of the beam [6,7] is emphasized as important parameter besides the coldness [8]. The two or three dimensional Magneto-Optical Trap is used in many experiments [2–4,6–12] as source of the production of intense, cold and low velocity atomic beam intended to be investigated and to be used in various applications.

In many experiments (see for instance [7]) the atomic beam is produced by expelling atoms from a MOT using resonance light beam. This beam excites the atoms and, as a result, pushes them into its direction of propagation. The return from the excited states through the spontaneous transitions results in heating of the atomic beam. This heat is partly removed by the cooling action of the operating MOT during the process of the leave. Consequently the temperature of the beam is expected to be always higher than that of the trap atoms.

To avoid this temperature increase as much as possible induced processes such as Adiabatic Rapid Passage (ARP) or π pulses are used to change the velocity of the atoms.

In the experiment [5] the atoms are cooled in a MOT to sub-Doppler temperature. After switching off the MOT light beams, the atoms are accelerated by applying counter-propagating laser beams of different frequency inducing ARP. Highly monochromatic atomic beam is produced but the number of ARP cycles and consequently the final momentum transferred to the atomic beam is restricted to about $100\hbar k$ where $\hbar$ is the Planck constant and k is the wave number. In a later experiment using similar arrangement as in [12] transfer of longitudinal momentum of about $50\hbar k$ was realized to the atoms [13].

It has to be mentioned that ARP was used in experiment of He* atom beam deflection [14] by the method originally proposed in [15]. The momentum transferred perpendicular to the He* beam propagation was $175\hbar k$.

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π pulses were also used for deflection of atomic beam [16]. The amount of the transferred momentum was about $700\hbar k$.

In all the above mentioned investigations using induced processes for acceleration or of deflection of atomic beams both the momentum and the scattering of the momentum (dispersion) of the atoms in direction of the accelerating light beam are small at the beginning of the interaction. The light beam induced process is used to change the momentum of the atoms but, at the same time, preservation of the initially small momentum scattering is of a primary interest. In other word the aim is to produce an atomic cold beam of well defined velocity.

How this aim can be realized depends strongly on the details of the interaction of the light beam at the beginning of the process of acceleration in the source of the atomic beam.

Because many times the MOT can serve as a very appropriate source of cold atoms, in the following, we investigate the process of the interaction of a train of counter-propagating frequency modulated light pulse pairs with ^{85}Rb atoms in MOT. The result of the interaction is the production of atomic beam after the atoms leave the potential valley of the trap.

The very beginning of the process of the acceleration of the atoms in the trap itself was investigated experimentally. Switching on the beam of frequency modulated counter-propagating light pulse pairs, the trap atoms start to be accelerated out of the magnetic zero field position of the trap. Every pulse of the train of light pulses interacts with the atom inducing transitions from the ground state to the excited state and the same pulse reflected by the end mirror, propagating in the backward direction, induces transition from the excited state to the ground state. If the probability of the transitions is 1 the momentum transmitted to the atom is $2\hbar k$ accelerating the atoms into the direction of propagation of the first pulse getting $2\hbar k$ momentum in every $\tau = 60$ ns according to the repetition rate ($n = 16.6$ MHz) of the pulses.

This method was proposed first by Nebenzahl and Szöke [15] to deflect atomic thermal beams. This deflection as the result of transfer of about $170\hbar k$ momentum in direction perpendicular to the atomic beam propagation was observed by Cashen et al. using similarly train of counter propagating light pulse pairs [14].

The peak intensity of the frequency-modulated laser pulses is far larger than that of the trap beams therefore the effect of the trap beams is neglected during the time of the pulse pairs (about 10 ns). The atoms remain under the action of the trap beams during the rest of the (60 ns) time interval between consecutive pulse pairs. The position and the shape of the cloud of atoms of the trap are measured by CCD camera with image intensifier detecting the intensity of the fluorescence light of the trap (atoms) at various time delay after the beginning of the pulse train of the frequency modulated pulses. The exposure time of the camera was usually 300 μs.

The position of the trap atoms is simulated by solution of the equation of motion taking into account the friction and the restoring force of the trap and the force of the train of the frequency modulated pulses. The results of the measurement and those of the simulation agree well if increased friction is assumed in case of the train of counter-propagating pulse pairs in comparison to the case of frequency modulated pulses propagating only in one direction.

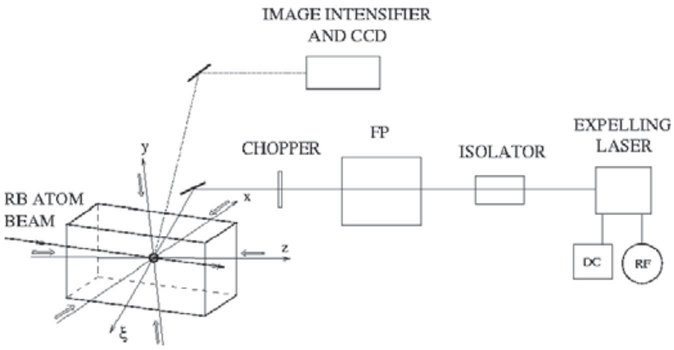

Fig. 1. The experimental set-up.

The interaction of the frequency-modulated pulses with the rubidium atoms is numerically calculated by solving the Bloch equations for the density matrix elements of the six hyperfine levels of the $5\,^2S_{1/2}$ and the $5\,^2P_{3/2}$ states. The intensity of the frequency modulated pulses needed for the adiabatic transition is determined on the basis of this calculation.

2 Experimental set-up

The trap is in a glass hollow right prism of dimensions $40 \times 40 \times 70$ mm. The prism is connected to a metal vacuum system consisting of two parts. One of these is the source chamber where the oven, the source of Rb atoms is located (see Fig. 1). The middle chamber is connected to the source chamber through a hole of diameter 5 mm and to the glass prism. The source and the middle chambers are pumped separately by two turbo pumps of 250 and 400 l/s speed. The vacuum in the source chamber is about 10^{-7} while in the middle part it is about 10^{-8} mmHg.

The source of the Rb atoms is an oven of known construction [17] consisting of two chambers separated from each other by aperture of diameter of 2 mm. The first chamber contains the Rb reserve and the Rb atoms entering into the second chamber through the aperture leave it through the next aperture being in the opposite wall. Atoms of velocity direction deviating from the one determined by the two aperture condensate in the second chamber and are recuperated into the first one through a narrow curved tube connecting the two chambers. The Rb source of this construction works for time duration of order of months without refilling i.e. without the need of the break of the vacuum.

The Rb atoms leaving the source through the two apertures and flying along the horizontal axis of the two vacuum chambers through the aperture separating the two chambers are trapped near the center of the glass hollow right prism. The magnetic quadruple field is produced by coils outside the glass prism with horizontal magnetic axis, and the same time, being perpendicular to the axis of the propagation direction of the atoms. The gradient of the magnetic field is 30 Gauss/cm.

Three circularly polarized laser beams retro reflected by mirrors forming $\sigma^+ - \sigma^-$ configuration crossing each other in the center of the quadrupole magnetic field and tuned to under the $5\,\mathrm{S}_{1/2}\,(F=3) \rightarrow 5\,\mathrm{P}_{3/2}\,(F'=4)$ resonance transition frequency of the ^{85}Rb atoms by about 10 MHz form the trap. One of the beams is horizontal (x-direction) propagating through the center of the coils perpendicular to the atomic beam. The second beam is almost horizontal (z-direction) deviating with a little angle from the horizontal plane. Accordingly, the third beam being perpendicular to both previous beams also forms the same little angle with the vertical direction (y-direction) as the second beam to the horizontal plane.

The light source of the trap is a laser diode with first facet antireflection coated in our lab and placed into an external grating tunable laser resonator of Littman configuration. The zero order beam of the grating is used as the output beam. The power of the laser on the wavelength of the rubidium resonance transition is about 20 mW which is distributed equally among the three trap beams. The diameter of the beams is 8 mm. The frequency of the laser is locked by 10 MHz offset to the resonance frequency of the rubidium atom as follows. A beam of small intensity is split from the beam of the trap laser and crosses the rubidium beam in between the trap and the source. The resulting fluorescence light is detected by photomultiplier (PM). The signal of the PM is used in the feedback loop for the lock-in frequency stabilization of the laser. The frequency offset of the laser from the resonance can be changed by changing the angle between the small intensity laser beam and the rubidium atomic beam. The temperature of the rubidium oven is measured by thermo element. The frequency offset is calculated by using the value of the measured angle between the small intensity laser beam and the rubidium atomic beam and the value of the mean velocity of the atoms calculated from the measured temperature. The precision of the calculated offset is about 10 percent.

The atoms from the other lower lying ground state $5\,\mathrm{S}_{1/2}\,(F=2)$ are re-pumped using the light of a second semiconductor laser without external resonator having wavelength corresponding to the transition $5\,\mathrm{S}_{1/2}\,(F=2) \rightarrow 5\,\mathrm{P}_{3/2}\,(F'=3)$. The wavelength of this laser is stabilized by saturation spectroscopic method using a glass cell containing rubidium [18].

The atoms are accelerated and expelled from the trap using a train of frequency modulated light pulses of duration of about 5 ns. Frequency modulated light is generated by sinusoidal modulation of the current of the semiconductor laser diode [14,19].

If the intensity of the light does not decrease fast enough before and after the resonance with the transition frequency of the atom, the adiabatic transition may cease to be fulfilled. Therefore pulses are formed from the frequency-modulated light by using a Fabry-Perot (FP) etalon. The etalon transmits the light of frequency being in the pass band of the etalon with center frequency tuned to resonance with the atomic transition. So pulses with a frequency chirp determined by the amplitude and frequency of the modulation are formed. The chirped pulses propagate in the horizontal plane, at small angle to the (horizontal) x beam of the trap. This beam is polarized horizontally. The modulation frequency can be changed in the 1 to 30 MHz range. The pass band of the etalon is centered both to the frequency of the transition $5\,^2\mathrm{S}_{1/2}\,(F=3) \rightarrow 5\,^2\mathrm{P}_{3/2}\,(F'=4)$ of the rubidium atom and in respect to the modulation, to the part of the central, fastest change of the sinus function. The width of the pass-band and the finesse of the etalon were about 500 MHz and 10 respectively. Usually the frequency of the modulation was 16.6 MHz and the chirp of the pulses formed was 3×10^{17} radian/s^2. The duration of the pulses formed was about 5 ns and the peak intensity was about 0.02 W at the exit of the interferometer. The train of the pulses was formed by a mechanical chopper. The duration of the train was 40 ms. The pulse train propagates to the trap and interacts with the trap atoms the second time after reflection on the end mirror. Consequently, each pulse of the train interacted two times with the atoms in the trap.

The position of the trap and the movement of the atom under the influence of the pulse train could be observed by two CCD cameras. The second camera was a free running CCD camera in near horizontal plane at about 45 degrees to both the x- and the z-axis about 20 degrees over the (x, z)-plane. This camera was used mainly for the visual observation of the trap.

The observation direction of the first camera is near to the vertical direction under the angle of about 20 degrees both with (x, y)- and (y, z)-planes. This camera was equipped with image intensifier and could be triggered. The exposure time was 300 μs and the starting time of the exposition could be fixed with 50 μs precision in the time window of the interaction of the frequency modulated pulses with the atoms (40 ms) or even outside this window, for instance, before it. The spatial observation window of the camera is 8×8 mm^2 at the location of the trap. The picture was digitized and stored in computer.

3 The physical model and the results of the measurements

Assumption is that there is no spontaneous decay during the time between the two light pulses of the pairs. Therefore, this time that is determined by the distance of the end mirror from the trap has to be short in comparison to the lifetime of the excited state of the atom. At the same time the first process i.e. the excitation induced by the first pulse has to be completed before the de-excitation induced by the returning pulse started. Therefore this delay-time cannot be too short. According to the numerical simulation of the process this delay-time is chosen to be 3 ns. For comparison, the lifetime of the excited state is 27 ns.

The result of the interaction with the pulse train is that the atoms start to move with a speed depending on the amount of the transmitted momentum in the interaction with one pulse pair and on the repetition rate. At the same time the trap beams cause friction and exert spring force to the direction of the center of the trap between consecutive pulse pairs. If the force of the trap beams attracting the atoms is smaller than the force of the train of the chirped pulses the atoms start to move out of the trap and be simultaneously under the influence of the restoring force of the trap (F_{trap}) and the expelling force (F_{expell}) of the chirped pulses and the friction force ($F_{friction}$) of the molasses caused by the trap beams. The force averaged on many chirped pulses is constant.

According to this, the acceleration of the atom ($a(\xi, t)$) into the direction of the expelling beams ξ is given as

$$ma(\xi, t) = F_{expell} - F_{friction} - F_{trap} \quad (1)$$

where

$$F_{expell} = n\zeta g. \quad (2)$$

The mass of the atom is m; $n = 1/\tau$ is the repetition rate of the frequency-modulated pulses. The momentum given to the atom by the laser pulse pair if each laser pulse would produce complete population transfer between the ground and excited states $g = g_2 = 2\hbar k$.

If the back reflecting mirror is removed i.e. only the forward propagating light pulse train interacts with the atoms then $g = g_1 = \hbar k$ is the momentum gained by the atoms in the process of the excitation.

We make an allowance that only ζ part of the g momentum is transferred to the atom $\zeta \leq 1$. In our simple model of the trap similarly to [20] we assume that the trap force, i.e. the restoring force (F_{trap}) and the friction force ($F_{friction}$) are given as

$$F_{trap} = f_1(4\hbar k/\Gamma)\beta\delta\varepsilon(dB/d\xi)\eta\xi \quad (3)$$

where

$$\eta = 1/\{[(\delta - kv - \varepsilon(dB/d\xi)\xi)^2/\Gamma^2 + 1 + \beta] \times [(\delta + kv + \varepsilon(dB/d\xi)\xi)^2/\Gamma^2 + 1 + \beta]\} \quad (4)$$

and

$$\beta = I/I_{sat}. \quad (5)$$

Similarly

$$F_{friction} = f_2(4\hbar k^2/\Gamma)\beta\delta\eta v. \quad (6)$$

I_{sat}, and δ are the saturation intensity of the $5\,S_{1/2}\,(F = 3) \rightarrow 5\,P_{3/2}\,(F' = 4)$ transition of rubidium atoms and the detuning of the trap beams. B and Γ are the magnetic field of the trap and the line-width of the transition. The velocity of the atoms is v. I is the intensity of the trap beams. The value of ε is calculated according to [21] and its value is 4.2×10^5 Hz/G for the case of linear polarization and $m_F = 3$. f_1 and f_2 factors are to be determined on the basis of the results of the experiments.

Figure 2 shows the displacement $\xi(t)$ of the center of mass of the atomic cloud depending on the time under the influence of frequency modulated pulse train calculated using the simple model outlined above (full line). In this case atoms are illuminated only by one beam propagating in the $+\xi$-direction. The repetition rate of the pulse train, the detuning and the intensity of the trap beams are $n = 16.6$ MHz and $\delta = 10$ MHz and $\beta = 2$.

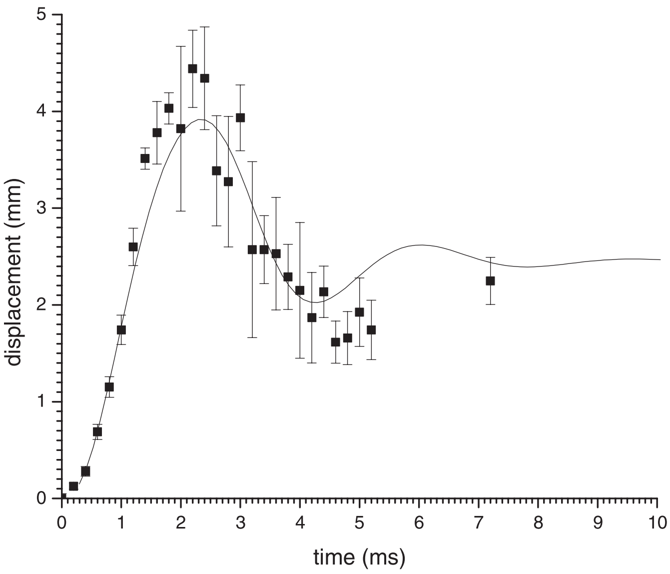

Fig. 2. The center of mass position of the atomic cloud depending on the time elapsed from the start of the train of frequency modulated light pulses propagating in the $+\xi$-direction. The continuous curve is the result of the simulation. The points with the standard deviations are the result of the measurement.

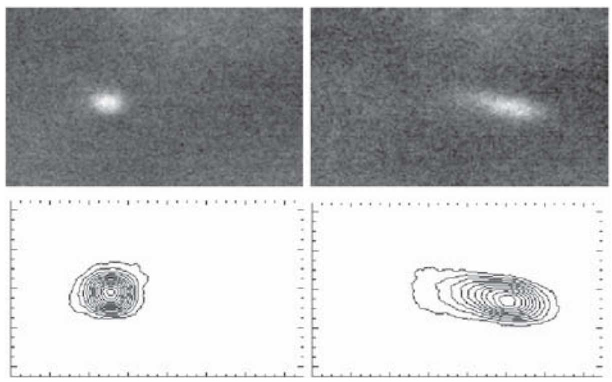

Fig. 3. Contour plot of the distribution of the atoms in the trap. Left: the distribution before the interaction with the frequency modulated pulse train. Right: the distribution of the atoms 3.1 ms after the start of the interaction with the train of frequency modulated pulse pairs.

The result of the experiment can be seen in the same figure. The dots represent the position of the center of mass of the trap atoms at the given time averaged over the duration of the exposition of the camera (300 μs) together with the standard deviations.

As an example, the spatial distribution of the atoms can be seen in Figure 3 as a contour map at 3.1 ms after the start of the pulse train (right part). The initial spatial distribution of the trap atoms before the pulse train is

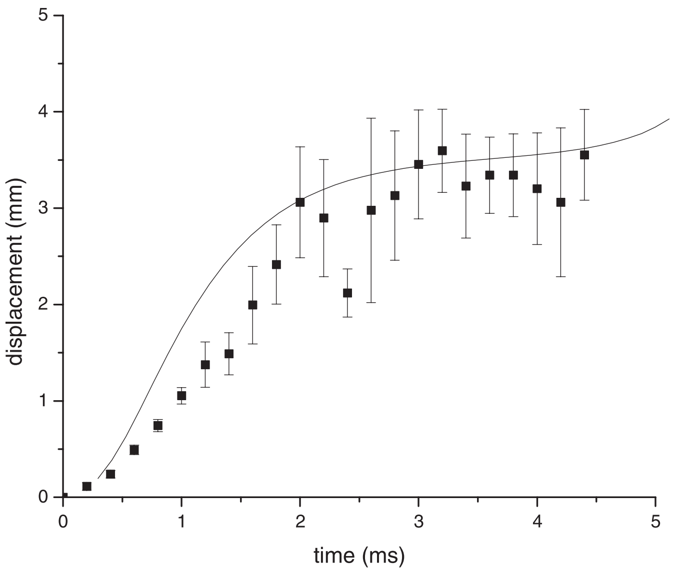

Fig. 4. The center of mass position of the atomic cloud depending on the time elapsed from the start of the train of frequency modulated light pulse pairs propagating in the $\pm\xi$-direction. The continuous curve is the result of the simulation. The points with the standard deviations are the result of the measurement.

shown in the figure (left part) to demonstrate the displacement of the trap atoms as they are measured by the first camera. The scales are arbitrary but they are the same in both figures.

In this work time dependent position of the center of mass of the trap atoms under the influence of a train of frequency modulated light pulse pairs is investigated. Apparently, there is some increase of the scattering of the spatial distribution of the atomic cloud under the influence of the train of the frequency modulated light pulse pairs (compare the right part with the left one of Fig. 3). This is expected because the atoms decaying to $5\,\mathrm{S}_{1/2}\,(F=2)$ ground state are re-pumped to the $5\,\mathrm{S}_{1/2}\,(F=3)$ state through absorption-spontaneous emission processes.

According to Figure 2 the atoms accelerated by the pulse train got to a new stationary position after some overshoot. The force $(n\zeta_1 g_1)$ caused by the excitation by the light pulses is not enough to expel the atoms from the potential valley of the trap. The decay following the excitation results in emission of light quanta in random direction. Consequently, the transferred momentum is zero in this spontaneous process in average.

Figure 4 shows the time dependent position of the center of mass of the trap atoms under the influence of a train of frequency modulated light pulse pairs. The first pulse of the pair propagates into the ξ and the second one into the opposite direction. The atoms leave the trap as the result of the interaction. The momentum $(\zeta_2 g_2)$ given to the atoms by the train of the pulse pairs is already enough to exceeds the height of the potential hill of the trap. The continuous curve shows the result of the solution of equation (1). The dots represent the result of the measurements together with the standard deviations.

That part of the curve outside the potential hill where the atoms start to get speed could not be measured partly because the scattered light intensity decreases with increased speed and because the atoms move out of the region illuminated by the trap beams.

On the one hand the ratio of the forces of the frequency modulated light beams acting on the atoms in the case of interaction with one $(F_{expell,1})$ and with both light beams $(F_{expell,2})$ is according to the result of the measurement

$$F_{expell,2}/(2F_{expell,1}) = \zeta_2/\zeta_1 = 0.66. \qquad (7)$$

This means that 66 percent of the atoms excited by the first pulse return to the ground state induced by the second pulse of the pulse pair. The deviation of this ratio from unity can partly be explained by the 3 ns delay between the forward and backward propagating pulses. During this time the decay of the excited state causes the transfer of about 20 percent of the excited state population to the ground hyperfine levels $F = 2$ and 3.

On the other hand the force $F_{expell,1}$ what one pulse alone exerts on the atoms is far smaller than the expected one when $\hbar k$ momentum is transferred by each light pulse. The calculated transferred momentum is $0.0455\hbar k$ i.e. $\zeta_1 = 0.0455$. In other words the exerted force is 4.55 percent of the expected one in case of one beam. Correspondingly the force is 7 percent of the expected one in case of the pulse pair acting.

Further problems that the measured results could be simulated assuming that the friction force $F_{friction,1}$ in case of one light pulse, $f_{2,1} = 1$, is half of the friction force in case of the two light pulses $F_{friction,2}$, $f_{2,2} = 2$. In other words the friction is higher when the forward and the backward propagating light pulses act simultaneously on the atoms. Further on, $f_{1,1} = f_{1,2} = 2$ was assumed in the simulations.

4 Computer simulation of the change of the population of levels during the interaction with chirped pulses

In order to get more detailed insight into the processes computer code of the Schrödinger equation was assembled to describe the temporal behavior of the populations, fine and hyperfine structure coherences of the six hyperfine, two ground $5\,^2\mathrm{S}_{1/2}\,(F=2,3)$ and four excited $5\,^2\mathrm{P}_{3/2}\,(F'=1,2,3,4)$ levels of the ^{85}Rb atoms [22]. In this calculation the upper ground state $5\,^2\mathrm{S}_{1/2}\,(F=3)$ and the $5\,^2\mathrm{P}_{3/2}\,(F'=2,3,4)$ levels of the rubidium atoms interact with the frequency modulated to and fro propagating light pulses of given peak intensity. The atoms decaying into the lower lying ground state are re-pumped by light being in resonance with the $5\,^2\mathrm{S}_{1/2}\,(F=2) \to 5\,^2\mathrm{P}_{3/2}\,(F'=3)$ transition similarly as in the experiment. The intensity of this re-pumping light is 1.8 mW/cm^2 approximately.

The phase of the trap beams was fluctuating because of the fluctuation of the position of the trap mirrors.

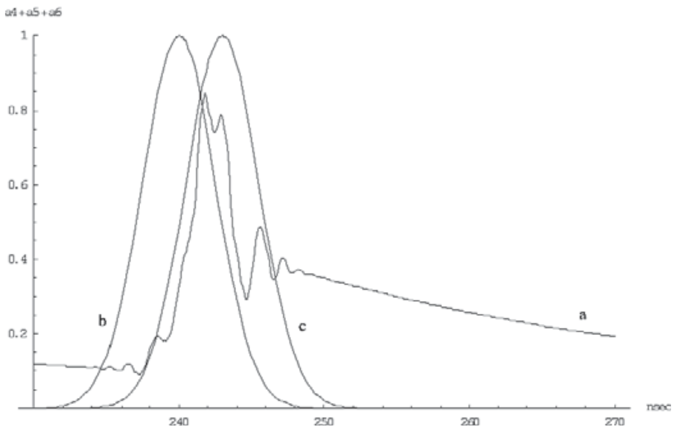

Fig. 5. Computer simulation of the interaction of frequency modulated pulse pairs propagating in $\pm\xi$-directions with ^{85}Rb $^2\mathrm{S}_{1/2}\,(F=3) \leftrightarrow {}^2\mathrm{P}_{3/2}\,(F'=2,3,4)$ transitions. The rubidium atoms are in the $^2\mathrm{S}_{1/2}\,(F=3)$ state at the beginning of the interaction. The chirp is 0.1 GHz/ns and the intensity is $i_{sur} = 0.456$ W/cm^2. Curve a: the sum of the populations of the $^2\mathrm{P}_{3/2}\,(F'=2,3,4)$ excited levels of ^{85}Rb atoms depending on time. The time is counted from the start of the interaction of the frequency modulated light pulse pairs. The population is normalized to 1. Curve b: the 4th light pulse of the train propagating into the $+\xi$-direction. The light pulse is normalized to 1. Curve c: the 4th light pulse of the train propagating into the $-\xi$-direction. The light pulse is normalized to 1.

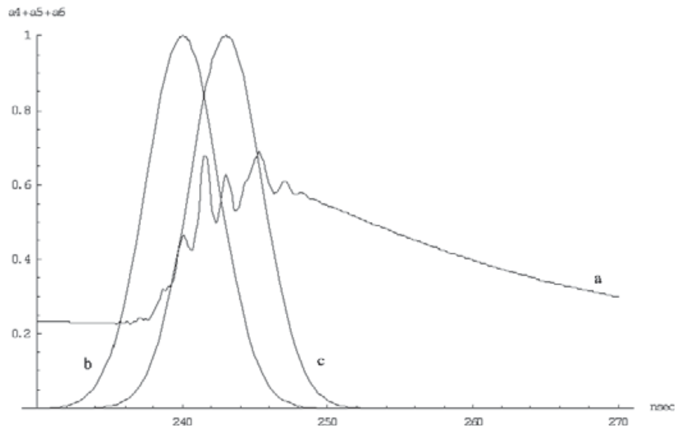

Fig. 6. Computer simulation of the interaction of frequency modulated pulse pairs propagating in $\pm\xi$-directions with ^{85}Rb $^2\mathrm{S}_{1/2}\,(F=3) \leftrightarrow {}^2\mathrm{P}_{3/2}\,(F'=2,3,4)$ transitions. The rubidium atoms are in the $^2\mathrm{S}_{1/2}\,(F=3)$ state at the beginning of the interaction. The chirp is 0.1 GHz/ns and the intensity is $i_{sur} = 0.912$ W/cm^2. Curve a: the sum of the populations of the $^2\mathrm{P}_{3/2}\,(F'=2,3,4)$ excited levels of ^{85}Rb atoms depending on time. The time is counted from the start of the interaction of the frequency modulated light pulse pairs. The population is normalized to 1. Curve b: the 4th light pulse of the train propagating into the $+\xi$-direction. The light pulse is normalized to 1. Curve c: the 4th light pulse of the train propagating into the $-\xi$-direction. The light pulse is normalized to 1.

Therefore only the populations and the coherences of the hyperfine structure levels were calculated with the appropriate statistical weights.

Figure 5 shows the sum of the population $(a_4+a_5+a_6)$ of the upper three levels $F'=2,3,4$ of the rubidium atom and the two light pulses counter-propagating to each other versus time (this is the fourth pulse pair in the train). The peak intensity (i_{sur}) of the beams and chirp (b_{fr}) are $i_{sur} = 456$ mW cm^{-2} and

$$b_{fr} = \pi a m_f f_r = 1 \times 10^8 \text{ Hz/ns}. \quad (8)$$

Here $f_r = 16.6$ MHz and $am_f = 1.9$ GHz are the frequency of the modulation and the frequency excursion i.e. the frequency range where the frequency of the light changes as the result of the modulation. In the figure, both the populations of the levels and the light pulses are plotted normalized to 1.

The first pulse produces sudden transition from the $F=3$ ground state to the excited states and the second pulse of the light pulse pairs induces a similarly fast transition back. This process repeats in 60 ns time interval. The delay between the two light pulses is 3 ns as in the experiment. Because of this delay some of the population decays spontaneously to the ground states and therefore the normalized population rise and the next drop is always smaller than one. Consequently the transferred momentum by one pulse pair is always smaller than $2\hbar k$.

It gets even less if the power of the chirped pulses increases. The time dependence of the population of the levels is not so smooth in time as in Figure 5. It contains modulation. Increasing the power causes oscillations between the excited and the ground states reducing the transferred momentum. See in this respect Figure 6 which is similar to Figure 5 except the intensity of the chirped pulses is increased by a factor of 2 ($i_{sur} = 0.912$ W/cm^2). Moreover, it is remarkable that the population grows continuously during the light pulses in spite of the oscillations and it starts to decay spontaneously at the end of the pulses. Therefore it can be guessed that the transferred momentum approaches to zero.

Moreover, the transition into the excited levels and back to the initial one (of the population) is as well-defined as shown in Figure 5 only in a relatively narrow interval of the intensity of the chirped frequency light.

Figure 7 shows the population change caused by the frequency modulated pulses of intensity $i_{sur} = 0.19$ W/cm^2 which is less by about factor 2 than the intensity in case of Figure 5. The result of the two pulses is only the excitation of the atoms but there is no induced de-excitation. The transferred momentum is probable less than $2\hbar k$ because the excitation is caused presumable by to and fro propagating pulses giving momentum into opposite directions. The excited atoms decay spontaneously afterward resulting in zero transferred momentum in this part of the process on average.

The scenario shown in Figure 5–7 resembles better to π pulse like transition in spite of the frequency modulation, i.e. in spite of the chirp (b_{fr}) being fast enough (see Fig. 3 in [23]).

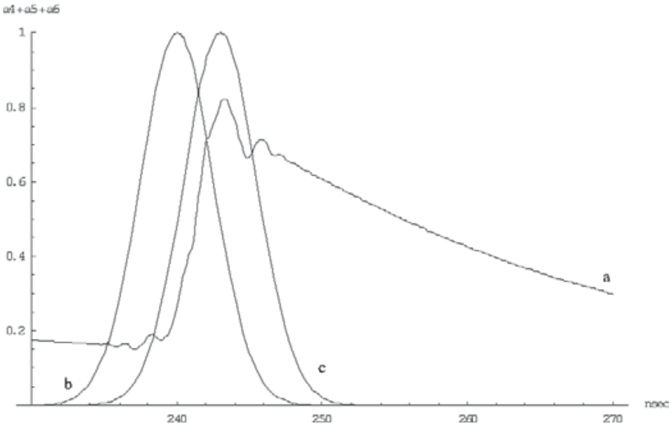

Fig. 7. Computer simulation of the interaction of frequency modulated pulse pairs propagating in $\pm\xi$-directions with ^{85}Rb $^2\mathrm{S}_{1/2}\,(F=3) \leftrightarrow {}^2\mathrm{P}_{3/2}\,(F'=2,3,4)$ transitions. The rubidium atoms are in the $^2\mathrm{S}_{1/2}\,(F=3)$ state at the beginning of the interaction. The chirp is 0.1 GHz/ns and the intensity is $i_{sur} = 0.19$ W/cm^2. Curve a: the sum of the populations of the $^2\mathrm{P}_{3/2}\,(F'=2,3,4)$ excited levels of ^{85}Rb atoms depending on time. The time is counted from the start of the interaction of the frequency modulated light pulse pairs. The population is normalized to 1. Curve b: the 4th light pulse of the train propagating into the $+\xi$-direction. The light pulse is normalized to 1. Curve c: the 4th light pulse of the train propagating into the $-\xi$-direction. The light pulse is normalized to 1.

The criterion for the adiabatic transition for two levels is fulfilled i.e.

$$R\tau > 1 \text{ and } b_{fr} < R^2.$$

$R = 0.6$ radian/ns is the Rabi frequency and $\tau = 5$ ns is the time duration at half maximum of the light pulse for the case of Figure 5 and the $5\,^2\mathrm{S}_{1/2}\,(F=3) \rightarrow 5\,^2\mathrm{P}_{3/2}\,(F'=4)$ transition.

Summarizing, the simulation shows (in the case of the hyperfine states of the ^{85}Rb atoms) that the adiabatic transition takes place in a well defined interval of the intensity if the chirp of the light pulses is fixed contrary to the common expectation. This interval is shifted upwards in intensity if the chirp increases. Outside this interval there are repetitive excitation and de-excitation of the atoms resulting in surprisingly very low, far lower than $\hbar k$, transferred momentum as the experimental result shows. To reach large transferred momentum, i.e. large acceleration of the atom the intensity of the pushing radiation and the chirp have to be simultaneously in well defined regions of these parameters. It seems that the adiabatic process is not as robust in our case as expected. I.e. it is not robust in the case of the simultaneous hyperfine transitions of the ^{85}Rb atoms as our simulation shows. To verify this statement experimentally in more details the chirp of the pulses has to be measured and made it changeable in a controllable way to determine the region of the intensity and that of the chirp where the transfer of the momentum from the field to the atom is maximal.

5 Summary

The movement of rubidium atoms in a magneto-optical trap under the influence of frequency modulated laser pulses of repetition rate of 16.6 MHz was investigated by using CCD camera of 300 μs exposure time and image intensifier. The force acting on the atoms is interpreted as the result of adiabatic transitions among the levels of the atoms. The experimentally observed force is far smaller than that expected.

The movement of the atoms is modeled under the action of chirped light pulses and re-pumping by continuous light by using numerical solution of the Bloch equations for the description of the excitation and de-excitation processes between two hyperfine ground states and the four excited hyperfine states. The calculation shows the following:

- at the basic parameters of the experiment i.e. at the given chirp rate and intensity of the light a more complete transition between the ground and the excited levels is expected and consequently the force should have to be larger than the observed one;
- the simulation shows that the adiabatic transition takes place only in a well defined, comparatively small interval of the light intensity in case of the given chirp rate contrary to the expectation.

As conclusion it can be stated that further measurements at various chirp rates are needed to find the region of the chirp and the intensity of the frequency modulated light pulses where the adiabatic excitation and de-excitation gives the maximal force for the acceleration of the atoms without temperature increase.

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