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The Magnesium Ramsey Interferometer: Applications and Prospects

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Abstract. In this paper it will be shown that an atom interferometer, based on the coherent splitting of the atomic wavefunction by four travelling waves (Ramsey interferometer), may be explained by a purely mechanical interpretation. As our first application of this Ramsey interferometer we have measured the phase shifts respectively *optical length* changes in a magnesium atomic beam caused by the acceleration of the partial atomic wave in one arm of the interferometer. This acceleration was achieved by the dipole force exerted by an off-resonant crossing laser beam which interacted with the ground state part of the wavefunction only. Further applications of this interferometer and improvements due to laser cooling will be discussed.

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With the recent developments of atom interferometers [1–5], matter wave interferometry has been extended to particles with many internal degrees of freedom. This opens up new experimental fields not or hardly accessible to neutron or electron interferometers taking advantage of additional interactions, e.g., with light fields.

In atom interferometers the atomic wavefunction is either split by mechanical, microfabricated beamsplitters (wavefront splitting in terms of optical interferometry) [1, 2], or by the interaction with light waves (amplitude splitting) [3, 5]. The splitting due to the redistribution of photons in a standing wave divides the wavefunction into partial beams of ground state atoms, differing in momentum by even multiples of the photon momentum $\hbar\mathbf{k}$ ($\mathbf{k}$: wavevector of the light field).

On the other hand, the splitting due to the absorption of a single photon from a travelling wave, in which atoms are excited to a reasonably long living state, will result in two partial beams, differing in momentum as well as in the internal states. This simplifies extraordinarily the selective access to one interferometer arm by state selective interactions, without the need for a spatial separation between the two arms (typically a few μm in atom interferometers based on mechanical beamsplitters) or a spatial limitation of the interaction to one arm.

Applications of atom interferometers [3, 5] presented so far have only been sensitive to interactions with the external degrees of freedom. In the experiment described here, we apply an additional light field to change the phase of the matter wave in one arm [6].

1 The Magnesium Ramsey Interferometer

Our interferometer setup consists of an atomic beam of magnesium atoms crossed perpendicularly by four travelling laser waves resonant with the intercombination transition $^1S_0$–$^3P_1$ of ^{24}Mg ($\lambda = 457$ nm, lifetime of the $^3P_1$ state $\tau = 4.6$ ms). This setup constitutes an atom interferometer as was first shown by Bordé [7].

The interactions with the four laser fields split and subsequently recombine the atomic wavefunction by the exchange of photon momenta and photon energy between the laser fields and the atom. Figure 1 shows those atomic trajectories which contribute to the interference. Each closed

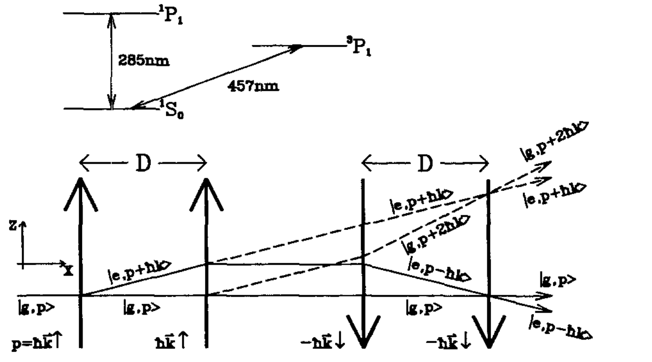

Fig. 1. The upper part shows the relevant part of the magnesium level scheme. The lower part shows the principle configuration of the Ramsey interferometer [7]. Solid lines: high frequency (blue) recoil component; dashed lines: low frequency (red) recoil component

loop represents an interferometer of the Mach-Zehnder type corresponding to the two recoil components. The two exit ports of both interferometers also differ in momentum and in the internal state. Therefore the interferometer can simply be read out by monitoring the excited state population, e.g., by detecting its fluorescence.

1.1 Mechanical Interpretation of the Ramsey Interferometer

Compared to atom interferometers working with material beamsplitters Ramsey interferometers offer the advantage that the beamsplitting can be affected by the laser frequency. In the following we will explain the frequency dependence of the interference pattern as effect of a momentum transfer perpendicular to the direction of the laser beams. This momentum transfer, which is widely neglected when treating the scattering of atoms by a laser field, plays a crucial role in the Ramsey interferometer. Due to the high interferometric sensitivity, small longitudinal displacements caused by different momenta in both arms strongly affect the interference. The momentum transfer with a component perpendicular to the laser beam is possible according to the Heisenberg minimum uncertainty between the rms waist radius Δw and the angular spread of photon momenta $\hbar\Delta k_x$, $\Delta w \hbar \Delta k_x = \hbar/2$ of a Gaussian beam. For simplicity we will consider only one interferometer (the blue recoil component, solid lines in Fig. 1).

Energy and momentum conservation for the absorption of a single photon with frequency ω_L demand

$$\mathbf{p}_0^2/2m + \hbar\omega_\mathrm{L} = (\mathbf{p}_0 + \hbar\mathbf{k})^2/2m + \hbar\omega_0\,, |\mathbf{k}| = \omega_\mathrm{L}/c\,. \quad \text{(1a)}$$

Here ω_0 denotes the atomic eigenfrequency, $\mathbf{p}_0$ the momentum of the incident atom in the ground state, and m the mass of the atom. Equation (1a) can be simplified to

$$\mathbf{k}\cdot\mathbf{p}_0/m = \Delta - \delta\,. \quad \text{(1b)}$$

This means that the atom absorbs a photon of the momentum decomposition of the localized field with the Doppler shift $\mathbf{k}\cdot\mathbf{p}_0/m$ compensating for the detuning $\Delta-\delta$, $\Delta = \omega_\mathrm{L} - \omega_0$ denoting the laser detuning and $\delta = \hbar\mathbf{k}^2/2m$ the single recoil shift. Thus for a detuning $\Delta \neq \delta$ a momentum component $\hbar k_x$ parallel to the atomic momentum and perpendicular to the laser beam is transferred to the atom.

If we assume the laser beams to be parallel to the z-axis (Fig. 1), the momentum transfer leads to a spatial displacement Δx and Δz of both partial waves $|g, \mathbf{p}_0>$ and $|e, \mathbf{p}_0 + \mathbf{k}>$ during the dark zone between the first and the second laser beam:

$$\Delta z = T\hbar k_z/m\,, \Delta x = T\hbar(\Delta - \delta - p_z k_z/m)/p_x\,. \quad \text{(2)}$$

Here $T = D/v_x$ denotes the time of flight between first and second respectively 3rd and 4th laser beam, p_x and p_z the atomic momentum along x and z, and k_z the mean laser wavevector component along z. During the central dark zone between 2nd and 3rd laser beam atoms in both partial waves are in the same internal and external state $|g, \mathbf{p}_0>$ ($|e, \mathbf{p}_0 + \hbar\mathbf{k}>$ for the red recoil component), leading to no additional displacement. In the third dark zone a momentum difference between both partial atomic waves leads to a final displacement at the exit ports of $\Delta z = 0$, $\Delta x = 2T\hbar(\Delta - \delta)/p_x$ ($\Delta x = 2T\hbar(\Delta + \delta)/p_x$ for the red recoil component). With our experimental parameters a laser detuning of one kHz corresponds to a longitudinal separation of the atomic wavepackets by $\Delta x = 300\,\mathrm{fm}$. In each interferometer this displacement leads to an interference term in the probability of finding the atom in one exit port which harmonically varies with the phase difference $\phi = 2\pi\Delta x/\lambda_\mathrm{dB}$ (λ_dB being the de Broglie wavelength $\lambda_\mathrm{dB} = h/p_0$) between both interfering arms. As the two exit ports correspond to different internal states, the probability P_e of finding an atom behind the interferometer in the excited state is given by

$$P_\mathrm{e} \propto \cos(\phi + \phi_\mathrm{L}) = \cos\left[2T(\Delta \pm \delta) + \phi_\mathrm{L}\right] \quad \text{(3)}$$

neglecting a constant background. The $+\delta$ corresponds to the red recoil component, the $-\delta$ to the blue one. Here $\phi_\mathrm{L} = \phi_2 - \phi_1 + \phi_4 - \phi_3$ is a phase depending on the relative phases $\phi_1, \phi_2, \phi_3, \phi_4$, of the four laser beams. This oscillation in the excitation probability describes the well known Ramsey fringe pattern.

The resulting amplitude of the interference fringes is given by the product of the individual excitation amplitudes in the subsequent interaction with all four laser beams.

The Schrödinger equation in the rotating wave approximation separates in a free motion along z with momentum $p_z - \hbar k_z/2$, $p_z + \hbar k_z/2$ for ground- and excited state, respectively, and a motion along x according to

$$\mathrm{i}\hbar\frac{\partial}{\partial t}\psi(x) = \left[-\hbar^2/2m\frac{\partial^2}{\partial x^2} + \hbar/2\begin{pmatrix} -\Delta' & \mathrm{e}^{\mathrm{i}\phi_i}\Omega(x) \\ \mathrm{e}^{-\mathrm{i}\phi_i}\Omega(x) & \Delta' \end{pmatrix}\right]\psi(x) \quad \text{(4)}$$

neglecting a weak divergence of the laser fields along z, i.e., for a Rayleigh range of the laser beams large compared to the transverse width of the atomic waves. Here $\Delta' = \Delta - \delta - k_z p_z/m$ denotes the effective detuning, $\Omega(x)$ denotes the Rabi frequency and $\psi = (\psi_\mathrm{e}, \psi_g)^\mathrm{T}$ denotes the atomic wavefunction. This equation can be further simplified if we look for stationary solutions and neglect the different momenta of both coupled states and the spreading of the wavepackets during the interaction (Raman-Nath approximation [8]), rendering

$$\mathrm{i}\hbar\frac{p_x}{m}\frac{\partial}{\partial x}\phi(x) = \frac{\hbar}{2}\begin{pmatrix} -\Delta' & \Omega(x)\mathrm{e}^{\mathrm{i}\phi_i} \\ \Omega(x)\mathrm{e}^{-\mathrm{i}\phi_i} & \Delta' \end{pmatrix}\phi(x) \quad \text{(5)}$$

with $\phi(x) = (\phi_\mathrm{e}|e, p_x>, \phi_\mathrm{g}|g, p_x>)^\mathrm{T}$. This is equivalent to the well known Schrödinger equation for a two level atom interacting with a laser pulse with a fictitious time x/v_x, which can be easily integrated to give the individual excitation amplitudes in each laser beam. In this approximation the results given here are equivalent to those found by Bordé et al. treating the Ramsey setup as sequence of four laser pulses in time [9]. Note that the amplitudes vary only slowly with the effective detuning Δ' as long as Δ' is small compared to the Rabi frequency Ω. Therefore the frequency dependence is mainly determined by the atomic evolution during the dark zones. When the spatial shift Δx surpasses the coherence length of the atomic beam (or the width of the corresponding wavepacket) the fringe amplitude disappears.

The transverse spatial separation of both arms in the interferometer depends for one atomic species on the longitudinal atomic velocity and the laser beam distance D (Fig. 1). For a typical configuration the separation will range from one to several hundred microns and is usually, but not necessarily, smaller than the diameter of the atomic beam.

2 Application as Frequency Discriminator

The sensitive dependence of the interference signal on the laser frequency has been the basis of the optical Ramsey spectroscopy for several years [10]. Typical widths of the central fringe range from several kHz up to several tens of kHz depending on experimental conditions and, according to (3), on the distance D between the copropagating pairs of laser beams.

Figure 2 shows the experimental setup of our Mg-interferometer. The effusive Mg atomic beam ($T = 700\,\mathrm{K}$) is collimated to a divergence of 3 mrad and the 457 nm beam is provided by a stilbene 3 dye laser (rms linewidth less than 200 Hz, drift 20 Hz/s). The laser beam is retroreflected by two cat's eyes forming the four Ramsey beams [10]. The fluorescence from the excited atoms is detected a few centimeters downstream the last laser beam by a photomultiplier. The two Ramsey fringe patterns formed by a superposition of both recoil components separated by 79.5 kHz for ^{24}Mg are shown in Fig. 3 with a distance D of $D = 12\,\mathrm{mm}$ resulting in a width of the central fringe of 12 kHz. Only the lowest order fringes are visible due to the low coherence length of the thermal atomic beam of about two de Broglie wavelengths ($\lambda_{\mathrm{dB}} = 23\,\mathrm{pm}$).

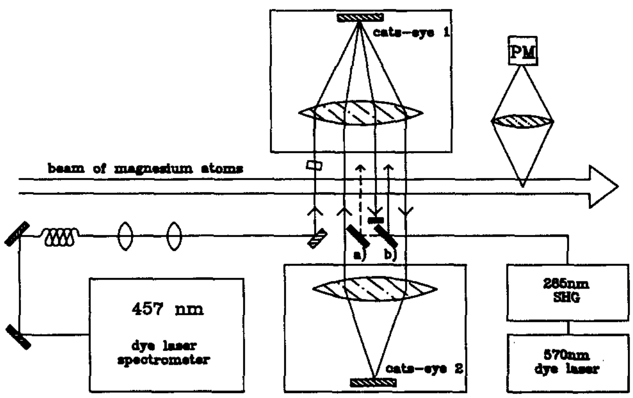

Fig. 2. Experimental setup. The 285 nm laser beam is used for the suppression of one recoil component (mirror at position a, laser on resonance with $^1S_0$–$^1P_1$ transition) or for an additional state selective potential (mirror at position b, laser detuned off-resonance)

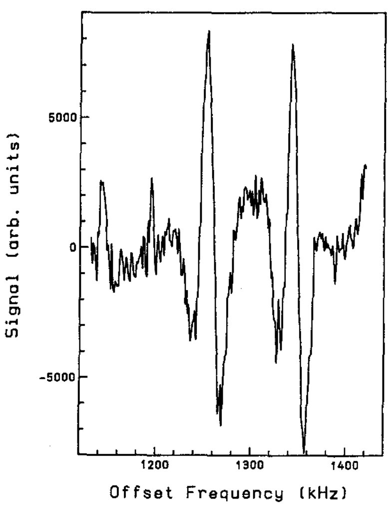

Fig. 3. Ramsey fringes observed in a Mg atomic beam ($D = 12\,\mathrm{mm}$). The signal is a superposition of the low and the high frequency recoil component. The incoherent Lamb dip background has been subtracted

3 Suppression of One Recoil Component

The excact determination of the line center frequency is complicated by the superposition of the fringe pattern of both recoil components. Thus it might be quite helpful for metrological as well as for interferometric applications to suppress one recoil component. This can be done by irradiating atoms in the central dark zone (Fig. 2 with the mirror in position *a*) with laser light tuned to the strong $^1S_0$–$^1P_1$ transition ($\lambda = 285\,\mathrm{nm}$, $\tau(^1P_1) = 2.02\,\mathrm{ns}$). In this region, atoms contributing to the blue recoil component are in the ground state. The resonant absorption of the 285 nm light deflects those atoms and moves them out of resonance with the following pair of 457 nm Ramsey beams. Even one spontaneous process at 285 nm would destroy the fringe pattern of one recoil component. The random momentum distribution of spontaneously emitted photons leads to a destructive momentum distribution of the finally interfering partial wave packets. But those atoms will still contribute to the incoherent part of the fluorescence signal.

Figure 4 shows experimental results demonstrating this effect; the suppression of the blue recoil component with a UV power of 10 mW is clearly visible. The UV laser was provided by frequency doubling a rhodamine 6G dye laser in ADA in an external ring cavity. The suppression of the

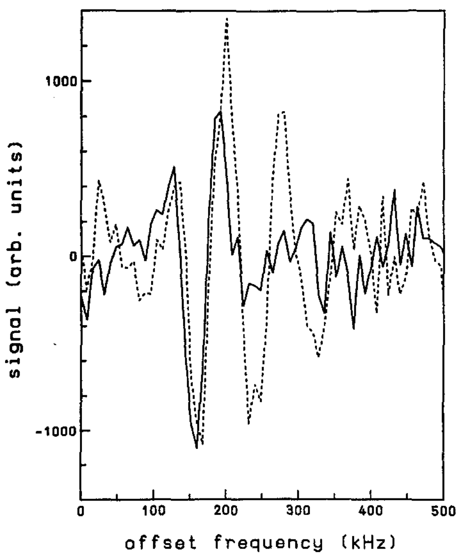

Fig. 4. Observed signals without (dashed line) and with additional 285 nm laser showing the suppression of the high frequency recoil component

red recoil component by an additional laser interacting with the excited state atoms was demonstrated for Ca atoms in [11].

4 Light Field as Phase Shifter for Atoms

In Sect. 1.1 it was shown that the interferometer may be explained by a longitudinal splitting of the atomic wave by the laser induced longitudinal momentum transfer to *parts of the atom*, which are labeled by the internal state. Because of this labeling it is rather obvious that by state selective interaction one partial wave can be selectively addressed by an additional laser beam. If this beam is an off-resonant Gaussian beam, it will be possible to decelerate or accelerate one partial wave by dipole forces in the inhomogeneous intensity profile.

In our experiment this additional state selective force, acting only on one arm of each interferometer, is introduced by a laser beam nearly resonant with the $^1S_0$–$^1P_1$ transition, which is sent into the dark zone between the third and the fourth Ramsey laser beam (Fig. 2 with the mirror in position *b*). Atoms in the ground state moving through the Gaussian laser intensity profile $I(x)$ will experience the optical dipole force. E.g., for red detuning of the laser, atoms will be accelerated towards the center of the beam and then decelerated again to their former velocity. This leads to an advance of this part of the wavepacket compared to that in the other arm of the interferometer. The corresponding potential U is the local energy of the ground state (the *dressed state* [12]) shifted by the interaction with the additional light field (ac-Stark effect)

$$U = \hbar\Delta_{\mathrm{UV}}/2[(1+\Omega^2/\Delta_{\mathrm{UV}}^2)^{1/2}-1]\,. \tag{6}$$

$\Omega = \Gamma(I/2I_{\mathrm{SAT}})^{1/2}$ denotes the Rabi frequency of the $^1S_0$–$^1P_1$ transition, $I_{\mathrm{SAT}} = \pi hc/(3\tau\lambda^3)$ its saturation intensity. For a sufficiently large detuning the spontaneous emission from the excited level $^1P_1$ can be neglected.

The resulting spatial shift Δx_{UV} between the two partial wavepackets can be calculated, with the help of Ehrenfest's theorem in the approximation that the additional potential is small compared to the atomic kinetic energy, to

$$\Delta x_{\mathrm{UV}} = -1/mv_x^2 \int U dx\,. \tag{7}$$

The corresponding phase shift $\Delta\phi_{\mathrm{UV}}$ is given by

$$\Delta\phi_{\mathrm{UV}} = 2\pi\Delta x_{\mathrm{UV}}/\lambda_{\mathrm{dB}} = -1/\hbar v_x \int U dx\,. \tag{8}$$

According to the small coherence length of the atomic beam, the spatial shift reduces the fringe contrast. As a detuning of the Ramsey laser also leads to a shift Δx_{R} of the wavepackets, the UV induced spatial shift Δx_{UV} of the wavepacket will be compensated if $\Delta x_{\mathrm{R}} + \Delta x_{\mathrm{UV}} = 0$. For the corresponding detuning of the Ramsey laser of

$$\Delta\omega_{\mathrm{L}} = -\int U dx/2\hbar D \propto P_{\mathrm{UV}}/\Delta_{\mathrm{UV}} \tag{9}$$

both wavepackets overlap completely (P_{UV} denotes the UV laser power). This means that the maximum contrast of the Ramsey fringes can be restored by an additional detuning $\Delta\omega_{\mathrm{L}}$ of the Ramsey laser. Note also that according to (6) and (9) the frequency shift is independent of the atomic velocity.

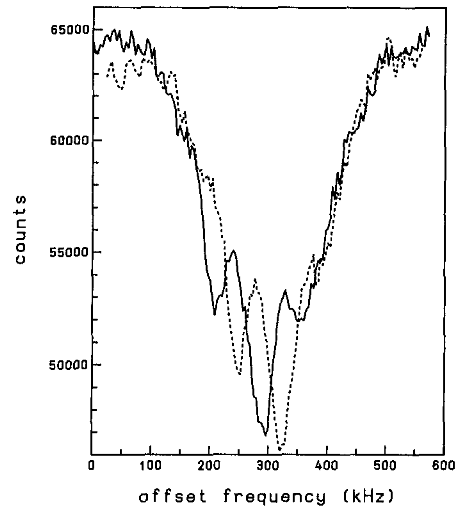

Fig. 5. Shift of the interference signal caused by an additional 285 nm laser, selectively interacting with only one arm of the interferometer. ($\Delta_{\mathrm{UV}} = 50\Gamma_{\mathrm{UV}}$, $P_{\mathrm{UV}} = 10\,\mathrm{mW}$). Dashed line with and solid line without 285 nm laser beam

The discussion above represents a mechanical interpretation of the ac-Stark effect. This view is better suited to matter wave interferometry than the traditional interpretation. In the regime where the light shift potential is small compared to the kinetic energy both views will lead to the same results (9).

A typical Ramsey spectrum demonstrating the light induced shift is shown in Fig. 5. The Ramsey signal was measured at each laser frequency with and without UV laser beam, in order to reduce the effect of any residual frequency drift on the 457 nm laser. It should be noted, that the Lamb dip remains unaffected, since it is the incoherent sum of excitation probabilities. We measured the shift for various detunings and intensities of the UV laser.

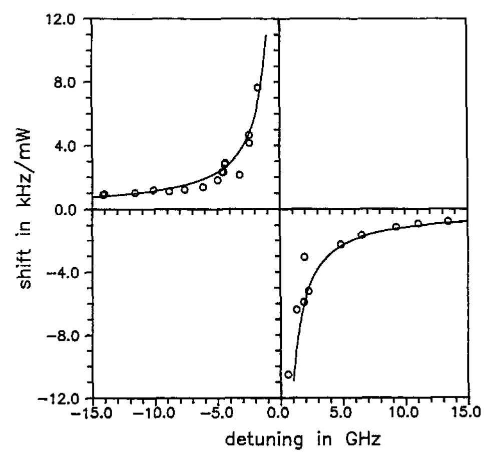

Fig. 6. Measured frequency shifts of the interference signal for various intensities and detunings of the additional 285 nm laser (285 nm laser waist 1.3 mm, $D = 4.5\,\mathrm{mm}$). Data have been normalized to a constant 285 nm laser power

These results are shown in Fig. 6; the solid curve shows the values calculated with (9).

The spontaneous emission probability increases with smaller detuning and higher power of the UV laser. This results in a decrease of the fringe contrast, since each spontaneous emission destroys the coherence and would allow us in principle to detect which path the atom took.

With a fringe amplitude of 3,000 counts per second and total signal strength of 20,000 counts per second we can measure a shift of 0.15 rad within one second.

The observed shift is actually a quantum nondemolition (QND) measurement of the photon number in the UV-laser beam. Due to the high sensitivity of matter-wave interferometers, which may be further improved using laser cooled and manipulated atoms, a detection of single photons inside a high finesse cavity seems to be feasible.

5 Improvements by Laser Cooled Atoms

Magnesium offers the possibility of laser cooling on the fast $^1S_0$–$^1P_1$ transition which constitutes a closed two level system. We decelerate a Mg atomic beam by the Zeeman tuning technique [13] within 12 cm to a final velocity in the range 50–200 m/s [14]. Figure 7 shows a typical final velocity distribution, which was measured by detecting the fluorescence induced by a second, counterpropagating 285 nm laser beam. The detected width of the signal of the decelerated atoms is mainly determined by the natural linewidth Γ_{UV} of the $^1S_0$–$^1P_1$ transition ($\Gamma_{UV} = 2\pi 80$ MHz). The actual width of the velocity distribution is less than 20 m/s.

5.1 *Interferometry*

The coherence length L_C of an atomic beam, e.g., the width of the atomic wavepackets, is given by $L_C = h/(m\Delta v_x)$. For a thermal atomic beam of Mg atoms ($T = 700$ K), the coherence length is 33 pm. In terms of optical interferometry this beam corresponds to white light and thus only low order fringes are visible. This situation can be substantially improved by laser cooling . For Mg atoms cooled to the Doppler limit the corresponding velocity spread Δv reads $\Delta v = 81$ cm/s. This is equivalent to a coherence length of 20 nm which is a factor of 600 larger than for a thermal beam.

Furthermore, also the mean atomic velocity can be reduced and tuned over a wide range by means of laser cooling techniques. This offers also a large tuning range of the corresponding de Broglie wavelength. In a matter wave interferometer slow atoms interact longer with a potential, hence they will experience a larger phase shift (see, e.g., (6)) compared to fast atoms; this leads to a higher sensitivity on small potentials.

5.2 *Frequency Discriminator*

For spectroscopic applications of the Ramsey interferometer the use of slow atoms reduces the fringe period $\Delta\omega = 1/2T = v_x/2D$ linearly with the mean velocity. The influence of the second order Doppler effect, which leads to a shift, an asymmetry and a reduction in the fringe contrast, is also diminished by cold atoms with a well known, narrow velocity distribution [10]. Therefore the application of laser cooled atoms will be of great importance for future metrological applications: for instance, resolving the natural linewidth of 35 Hz of the $^1S_0$–$^3P_1$ transition with a thermal atomic beam would require a distance between the Ramsey laser beams of $2D = 3.3$ m (neglecting the broadening due to the quadratic Doppler effect of 2 kHz!), whereas for laser cooled atoms with a velocity $v_x = 10$ m/s a seperation of 4.6 cm would be sufficient.

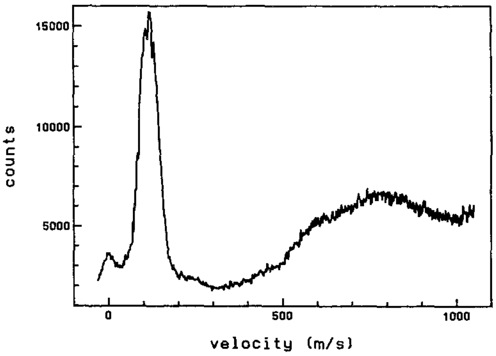

Fig. 7. Final velocity distribution of a laser decelerated and cooled Mg atomic beam

6 Interferometry with Trapped Atoms

Trapped atoms offer the possibility of substantially prolonged interaction times compared to those of beam experiments.

For trapping of neutral magnesium atoms a magnetooptical trap [15] is well suited. The trap, composed of six orthogonal 285 nm laser beams and a spherical magnetic quadrupole field, will narrow both the spatial and the momentum distribution to the Doppler limit ($\Delta v = 81$ cm/s). If this cold and dense ensemble of atoms is irradiated by successive, coherent pulses of two counterpropagating laser beams as shown in Fig. 8, we have a situation similar to the spatial sequence of four Ramsey laser beams in the atomic beam experiment. Thus the atomic waves are split and recombined *in place*, neglecting a slight motion due to the photon recoil.

Such a cycle could be started with the filling of the trap during a short time. Then the trapping lasers and the magnetic field would be switched off to allow the application of a 457 nm $\pi/2$ pulse to the atoms. After a time T a second $\pi/2$ pulse would be applied from the same direction, followed by the same sequence from the opposite direction. The subsequent detection of the excited state population by monitoring the fluorescence is very effective since all excited atoms decay within a small volume compared to the long decay length in an atomic beam.

The interference is based on the difference between the atomic coherence, which evolves with the atomic eigenfrequency, and the frequency of the laser pulses.

This scheme offers the opportunity for ultrahigh resolution spectroscopy due to the possible long pulse separation,

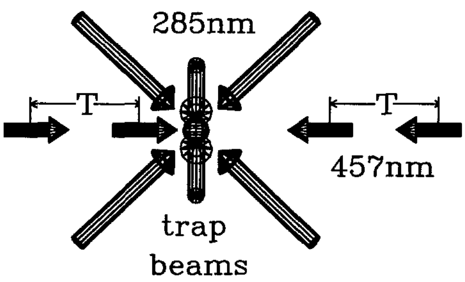

Fig. 8. Principle configuration of a pulsed Ramsey interference experiment on atoms captured in a magnetooptical trap

and it can also be used for the interferometric measurement of very small potentials.

If the trapping lasers are switched on for a short time after the first pair of pulses, the blue recoil component will automatically be suppressed.

7 Conclusion

We have shown that the Ramsey interferometer may be interpreted quite naturally by a mechanical splitting and recombination of the atomic wave in crossing resonant light fields. This picture immediately allows the estimation of typical interferometric quantities like coherence length, coherence time, contrast, etc., as well as the consideration of various influences by other phase changing interactions. We have demonstrated the phase shift in one interferometer arm caused by the dipole force of an additional laser beam. In addition it was possible to suppress one recoil component by eliminating one of the two Ramsey interferometers. With an experimental width of the central fringe of 12 kHz we can measure phase shifts of 0.15 rad within one second.

The rich internal structure of atoms in combination with the high sensitivity of the Ramsey interferometer will allow further fundamental experiments such as studies of Berry's phase in complex topologies, tests of general relativity, or searches for a fifth force. Especially laser cooled and trapped neutral atoms in a pulsed Ramsey geometry will open up totally new fields in high precision atom interferometry.

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