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CONCEPTS OF TEMPORAL MACH-ZEHNDER INTERFEROMETRY WITH ATOMS[1]

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The possibility of building a Mach-Zehnder type atomic interferometer within a magneto-optical trap is presented here. We propose trapping ^{7}Li atoms and subsequently applying a pulsed laser beam to the trap region. By a judicious choice of pulses and delays a *temporal*, three light diffraction gratings atomic interferometer can be obtained.

1. Introduction

During the past decade there has been a huge surge in the interest expressed by the physics community in the field of atom optics. This has resulted in the successful design and construction of numerous atom optical devices which facilitate the manipulation of and control over atoms. Beam-splitters, mirrors and diffraction gratings for atoms have made the realisation of atomic interferometers possible and several different techniques have been adopted for this purpose. For a review of the developments made in the field in the past few years the reader is referred to [1] and [2].

Recently, in our laboratory, an atomic interferometer using three standing light waves as diffraction gratings has been constructed for a thermal beam of metastable argon atoms [3] [4]. The atomic waves are divided at the first standing light wave and a coherent superposition of mainly zero and first order diffraction components is obtained. These components then pass the second standing light wave which alters their direction such that they overlap at the third grating. A number of beams emerges at this point, some of which are coherent superpositions of different trajectories through the three light gratings and, thus, form an interferometer. Interferences are detected

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by displacing the third grating along the direction of the laser light. This arrangement is equivalent to a Mach-Zehnder type three-grating interferometer.

We propose extending this experimental technique in order to build a similar interferometer in the time domain for magneto-optically trapped lithium atoms. The three light diffraction gratings will consist of three standing waves crossing the trap region at the same position in space but at different times. The first two waves will have the frequency shifted by equal amounts from the frequency of the third wave. The atoms, being quasi-stationary in the time scale considered, interact with each grating successively as a consequence of the sequential pulsing of the light gratings. Some of the more interesting features associated with the proposed experiment, including its "white-light" nature and its insensitivity to stray magnetic fields, will be discussed.

2. Experimental Considerations

The experimental arrangement which we will use consists essentially of a magneto-optical trap [5] optimised for the capture of lithium atoms. Work on this is already underway in the laboratory. A beam of lithium atoms is produced by heating an oven to $350 - 400°C$. The atomic beam is then trapped using a standard magneto-optical trap in which three orthogonal, retroreflected, circularly polarised, standing light waves and a magnetic field gradient provide the trapping mechanisms. The magnetic field is produced by a pair of anti-Helmholtz coils, arranged so that the zero-field at the centre of the coils defines the trap region. The measured magnetic field gradient along the propagation axis of the atomic beam is $30G/cm$ for a current of $30A$. We use the $2^2S_{\frac{1}{2}}(F=2) \leftrightarrow 2^2P_{\frac{3}{2}}(F=3)$ transition at $671nm$ [6]. The six trap beams have intensities of $20mW/cm^2$ and are all at the same frequency. The laser light, provided by an Ar-Ne pumped dye laser, is detuned off-resonance by $10MHz$ to the red. The entire experiment is housed in a vacuum chamber maintained at UHV ($\sim 5\text{x}10^{-9}$Torr with lithium in the system). From previous work carried out with ^{7}Li traps in our group [7] a life-time of $\sim 3s$ is expected for the trapped atoms. An atomic density of $10^{11}/cm^3$ and a velocity of $60cm/s$ should also be obtainable.

Next we consider the actual construction of the temporal interferometer within the trap. The trapping light beams must first of all be switched off. The trapped atoms are initially distributed over the two ground state hyperfine levels ($F = 1$ and 2). These atoms must be optically pumped to the $F = 1$ ground state level via the $2^2P_{\frac{3}{2}}$ excited state. One chooses a pumping beam on-resonance with the $2^2S_{\frac{1}{2}}(F=2) \leftrightarrow 2^2P_{\frac{3}{2}}(F=3)$ transition with frequency ν_1 (Fig. 1). Under these experimental conditions the hyperfine structure of the excited state can be ignored and it can be treated as a single state with a natural linewidth of $\sim 18.54MHz$.

Once the atoms are pumped to the lower ($F = 1$) ground state level the intensity of the laser beam is increased and a quick pulse of light of $100ns$ duration, obtained using an AOM, is applied to the trap. This first light pulse acts as the first diffraction light grating through which the atoms pass in the *time* domain. A momentum transfer of $2\hbar k$ results in a coherent separation of the atomic wave impinging on the grating into primarily, zero and first diffraction order beams. A schematic representation of the interferometer, in which one can see the three light gratings, and the zero and first diffraction order beams (corresponding to momentum kicks of 0 and $\pm 2\hbar k$ parallel to

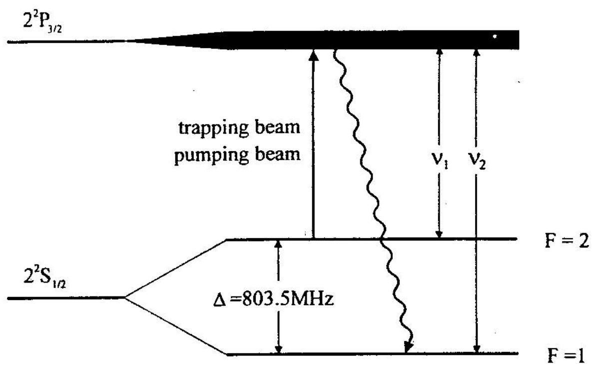

Fig. 1. Energy level diagram for ^{7}Li showing the two ground state hyperfine levels separated by 803.5MHz and the excited state. The resonance frequency, ν_1, corresponds to the transition from the $F = 2$ ground state level to the excited state and has a wavelength, $\lambda_{opt} \sim 670.96nm$. $\nu_2 = \nu_1 + \Delta$.

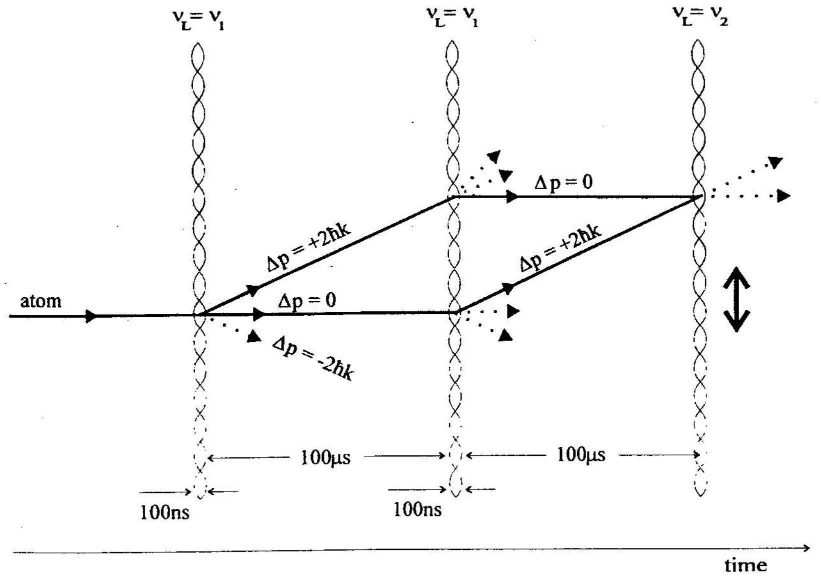

Fig. 2. Schematic representation of the three light diffraction gratings showing the zero and first diffraction orders only. Δp corresponds to a momentum transfer to the atoms parallel to the standing light waves. ν_L is the laser frequency. Note that the interferometer is drawn as a function of time.

the standing light waves), is shown in Fig. 2.

The different atomic trajectories then freely evolve for $100\mu s$ before the second ν_1 light pulse of duration $100ns$ is applied. This acts as the second light grating for the atoms, which experience once more a momentum kick of $2\hbar\vec{k}$. Some of the diffracted beams are redirected and they freely evolve for a further $100\mu s$. After this time the beams overlap and an interference pattern can be observed. A third light pulse with a frequency $\nu_2 = \nu_1 + \Delta$ is applied in order to produce the third grating in the interferometer. Laser light with a frequency ν_2 is obtained by passing the ν_1 light (as used for the first two light gratings) through an EOM and selecting the positive, first order optical side-band with a fixed detuning of Δ. Thus the frequency of the third pulse is shifted with respect to the first two pulses, and the intensity of the light is lower. By a displacement of this light grating parallel to the standing wave one should observe intensity modulations in the light. We thus will obtain a Mach-Zehnder type atomic interferometer *in time*, in which the usual roles played by matter and radiation have been reversed. Since the internal state of the atoms remains unaffected, this can be classified as a de Broglie wave (centre-of-mass) interferometer.

It is important to emphasize that there will be no spatial separation between the three light gratings, and the successful operation of this interferometer relies entirely on the temporal evolution of the trapped ^{7}Li atoms and the sequential pulsing and frequency selections of the laser light which produces the three gratings through which the atomic wave is coherently split by diffraction, redirected and finally recombined.

3. Discussion

In the atomic Mach-Zehnder interferometer in the time domain presented here, the atoms are diffracted at near-resonant standing light waves. It has been shown [8] [9] that this can be treated as diffraction from a sinusoidal phase grating and, therefore, the strength of the diffraction orders depends on the Rabi frequency (i.e. the light intensity) and the detuning, Δ. Thus, the characteristics of the diffraction gratings in the proposed interferometer can be changed by varying either of these parameters. In addition the period of the light grating, which is given by $\lambda_{opt}/2$ where $\lambda_{opt} \approx 671nm$, can easily be changed by varying the frequency of the laser light.

A distinct advantage of using light gratings rather than material gratings in atomic interferometry lies in the fact that interferometers *in time*, as described above, can be constructed. However, in general, the separation between the diffracted beams will not be large enough to result in separated wave-packets. The interaction times of the atoms passing through such an interferometer are identical irrespective of the atomic velocity. This non-dispersive, "white-light" nature allows us to choose the diffraction regime (Bragg or Raman-Nath) in which we operate the apparatus by varying the light pulse duration and thus, changing the atom-light interaction time. In addition, the time of evolution between two successive light gratings can be very long since it depends only on the delay-time between two light pulses.

Generally, the grating alignment in interferometers is extremely critical for observing interference effects. We expect to overcome this problem since in the proposed design all three light gratings occupy the exact same position in space and, thus, any stringent requirements with respect to their relative alignment are removed. Additionally, any vibrations of the mirror used as the retroreflector for producing the standing light-waves can result in overall phase-shifts to the interference pattern. To avoid this, the mirror should be properly mounted so that it is adequately isolated from all vibrations of the experiment. It has been shown that if the amplitude of mirror displacements due to the vibrations is small enough the measured contrast of the interference pattern will be reduced. Finally, due to the small size of an interferometer built within a MOT, it is expected that the strength of any stray magnetic fields will be sufficiently constant over the entire dimensions of the interferometer. Therefore, such an interferometer should be quite insensitive to the presence of stray fields.

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