Coherent Frequency Shift of Atomic Matter Waves

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We demonstrate how Bragg diffraction of atomic matter waves at a time-modulated thick standing light wave can be used to coherently shift the de Broglie frequency of the diffracted atoms. The coherent frequency shift is experimentally confirmed by interferometric superposition of modulated and unmodulated atoms resulting in time-dependent interference fringes. Our frequency shifter for atomic matter waves is a generalization of an acousto-optic frequency shifter for photons. [S0031-9007(96)01871-6]

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Investigations of time-dependent matter wave phenomena are a current field of research in order to study fundamental predictions of quantum theory. In neutron optics such experiments have been performed in recent years. Neutrons were deflected by time-dependent mirrors [1,2], slowed by diffraction at moving gratings and mirrors [3], or sent through time-dependent potentials [4]. Recently, experiments have been performed with atomic matter waves [5,6] where atoms released from a magneto-optical trap were reflected by a vibrating mirror. Many frequency sidebands of the reflected de Broglie waves have been detected in these experiments.

In the present Letter we demonstrate an easy modulation technique for a continuous atomic beam, where, in contrast to [5,6], the interaction time between the atoms and the light field is much larger than the temporal modulation period. Temporal diffraction in this regime can be viewed as the time equivalent of spatial Bragg scattering.

We start by comparing our time-modulated scattering experiments with standard Bragg diffraction [7–10]. An important feature of Bragg diffraction is its angle and velocity selectivity, and the appearance of only one diffracted beam, in contrast to diffraction at thin gratings [11,12] (Raman-Nath regime). Atoms are only diffracted if their velocity is matched to their incidence angle at the standing light wave, the "light crystal," by the Bragg condition; otherwise they just traverse the light field without deflection. This is demonstrated in the Bragg diffraction experiments plotted in Fig. 1. In case (A) the incidence angle of the atomic beam is the static Bragg angle (17.7 μrad). Two peaks result, corresponding to diffracted (arrow) and transmitted atoms, respectively. (B) shows the same experiment for atoms incident at an angle which differs by 44.2 μrad (approximately 2.5 Bragg angles) from the stationary Bragg angle. Only the peak of transmitted atoms is obtained.

A new observation is presented in (C). Here, the atoms are incident at the same detuned angle as in (B), but additionally the intensity of the standing light wave is modulated with a specific frequency (75 kHz) which is matched to the detuning of the incidence angle as explained below. Now, diffracted atoms are observed again (arrow) at the same position as in the case (A) of static diffraction. Thus, a particular intensity modulation frequency of the standing light wave compensates a detuning of the Bragg angle and retrieves the conditions enabling diffraction. We will show later that the de Broglie frequency of these "dynamically" diffracted atoms is shifted from the frequency of the incident atoms by the intensity modulation frequency, with a sign depending on the sign of the diffraction order.

For an explanation we first examine the usual case of static Bragg diffraction. The standing wave is a superposition of two counterpropagating light beams with

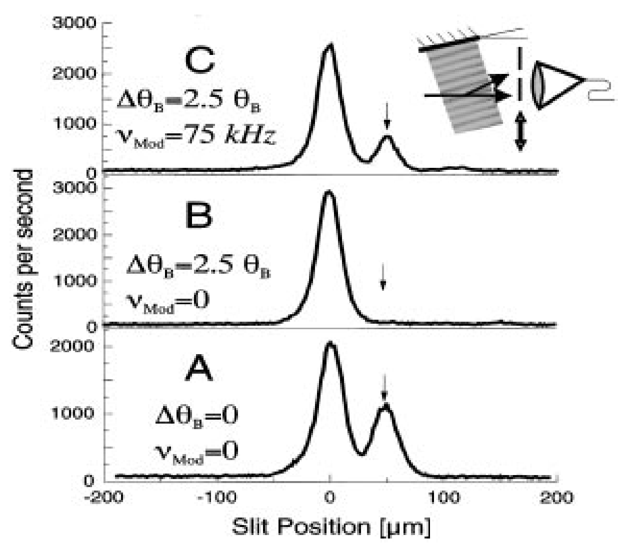

FIG. 1. Spatially resolved Bragg-diffraction pattern as a function of the scanning slit position (see inset) obtained with the setup of Fig. 2. In (A) the incidence angle of the atomic beam at the light wave is exactly the static Bragg angle (17.7 μrad). The two peaks correspond to the transmitted and the diffracted atoms (arrow), respectively. (B) shows the same experiment at a mirror angle detuned by 44.2 μrad ($\sim 2.5 \times \theta_B$). In (C) an additional intensity modulation frequency of 75 kHz is applied to the standing light wave, at the angle of (B). This restores the wave matching condition, and the peak of diffracted atoms reappears.

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wave vectors $\pm\vec{k}_L$ resulting in a grating period of $d_G = \pi/k_L$. The light frequency is detuned from an atomic transition frequency, such that spontaneous emission is insignificant, and the standing light wave acts like a pure refractive index crystal on the atomic de Broglie wave. In the time-independent case Bragg diffraction conserves the kinetic energy of the atoms $|\vec{k}_A| = |\vec{k}_A'|$ (elastic scattering) but changes the direction of the atomic momentum by two photon recoils $\vec{k}_A + 2\vec{k}_L = \vec{k}_A'$. Here, $\vec{k}_A$ and $\vec{k}_A'$ are the wave vectors of the incoming and the diffracted de Broglie waves, respectively. This leads to the condition that first order diffraction can occur only at a specific incidence angle, θ_B, which fulfills the Bragg condition, $\sin(\theta_B) = k_L/k_A$.

Interestingly, this condition can alternatively be interpreted in a different way: Bragg diffraction can be seen as a transition in a two-level system consisting of a diffracted and an undiffracted state. An incoming atom interacts with the light field via a process of absorption of a photon out of one component of the standing light field and of immediate reemission into the counterpropagating component. This process changes the momentum of the atom by two photon momenta $2\hbar\vec{k}_L$. Viewed in an inertial system where the incident atoms are at rest, the diffracted and the undiffracted states are separated by the "two-photon" recoil frequency, ω_{rec}, linked to the momentum change,

$$\omega_{\text{rec}} = \frac{2\hbar k_L^2}{m}, \qquad (1)$$

where m is the mass of the atom. In our experiment $\omega_{\text{rec}} = 2\pi \times 30$ kHz. A transition between the two states can be excited by applying this two-photon recoil frequency.

In static Bragg diffraction such a harmonic excitation with frequency ω_{rec} is due to the atomic trajectory crossing the spatially modulated light intensity grating. An atom incident at the Bragg angle needs the time $\tau = \pi m/\hbar k_L^2$ to traverse one period of the light intensity grating. Thus, in its rest frame the atom experiences an intensity modulation frequency of $\omega_{\text{spat}} = 2\pi/\tau = 2\hbar k_L^2/m$ which is exactly the two-photon recoil frequency ω_{rec} [Eq. (1)] required for a Bragg excitation. Because this is a static experiment, no energy is transferred to the atoms in the laboratory frame—the Bragg transition occurs between two states of the same energy but different momentums (directions).

The inverse case is an experiment where atoms are at rest in a standing light field [13], and are scattered if an appropriate temporal intensity modulation with frequency ω_{rec} is applied. In contrast to static Bragg diffraction, such a scattering is coupled with an energy transfer, which is supplied by the time-dependent excitation.

Our experiment is a link between these two cases. The angle of incidence of the atomic beam θ at the light grating is detuned from the static Bragg angle, $\theta = \theta_B + \Delta\theta$. The intensity modulation frequency, ω_{spat}, experienced by the atoms due to their passage through the spatially periodic light grating is now

$$\omega_{\text{spat}} = 2k_L \frac{\hbar k_A}{m} \tan(\theta_B + \Delta\theta) \approx \omega_{\text{rec}} + 2k_L \frac{\hbar k_A}{m} \Delta\theta$$

for small θ. This is not the two-photon recoil frequency of Eq. (1) required for a Bragg transition. However, by an additional intensity modulation of the light wave with frequency ω_{mod}, we produce a beating between ω_{spat} and ω_{mod} resulting in a sum and a difference frequency $\omega_{\text{beat}} = \omega_{\text{mod}} \pm \omega_{\text{spat}}$ experienced by the atoms. Thus, two resonances of ω_{mod} appear, at which ω_{beat} equals the two-photon recoil frequency required for Bragg diffraction,

$$\omega_{\text{mod}} = \pm 2k_L \frac{\hbar k_A}{m} \Delta\theta = \pm\omega_{\text{rec}} \frac{\Delta\theta}{\theta_B}. \qquad (2)$$

Momentum conservation then requires that in the laboratory frame the frequency of the de Broglie wave diffracted at the temporally modulated intensity grating is shifted by the intensity modulation frequency, ω_{mod}.

Figure 2 shows a schematic of our experimental setup (see also [14]). Metastable argon atoms with a mean thermal velocity of 690 ms^{-1} and with 60% FWHM are produced by a dc gas discharge. The beam is collimated to $\Delta\theta = 6$ μrad (FWHM) by a 10 μm slit and a 5 μm slit separated by 1.3 m, yielding a transverse momentum spread of 0.35 $\hbar k_L$ (FWHM). After the second slit the atoms interact with a standing light wave produced by retroreflection of a collimated expanded laser beam (diameter: 6 cm, intensity: 20 mW cm^{-2}) at a plane mirror. The laser light (linewidth: <2 MHz) is detuned by 2 GHz (~300 linewidths) from the 811 nm closed transition of the argon atoms, and thus the standing light wave acts as a thick refractive index grating for the incoming matter waves. The intensity of the laser light can be modulated using an acousto-optic intensity modulator (AOM) with rates up to 300 kHz. The angle of the retroreflection mirror can be tuned in a range of 300 μrad by tilting the

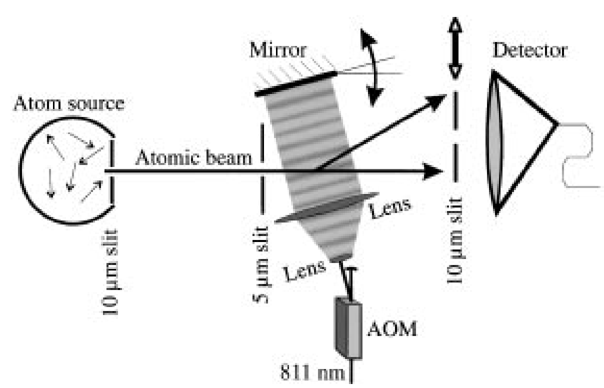

FIG. 2. Experimental setup (not to scale). A collimated thermal beam of metastable Ar atoms crosses a standing light wave. Diffracted and transmitted atoms are registered by a channeltron detector. The angle between atomic beam and light wave can be varied by tilting the mirror. The intensity of the laser light can be modulated by an acousto-optic modulator (AOM).

mirror mount with a piezo actuator with μrad resolution and an absolute precision of 8%. For an atomic beam incident at the first order Bragg angle ($\theta_B \sim 18\ \mu$rad) both the diffracted and the transmitted atoms traverse $\sim$3 light intensity grating planes. Behind the interaction region the atoms travel 137 cm to allow spatial separation of diffracted and transmitted atoms. The metastable atoms are registered by a channeltron detector in front of which a 10 μm slit is scanned in order to provide spatial resolution. The atomic intensity is measured as a function of the scanning slit position.

A more detailed study of time-dependent Bragg scattering is shown in Fig. 3. In these experiments the position of the scanning slit is held fixed at the position of the arrows in Fig. 1, such that only diffracted atoms are detected. The intensity of the diffracted atoms is measured as a function of the mirror angle. The top graph of the series shows the result for an unmodulated light crystal. Only one peak at the static Bragg angle is observed. Its width is determined by the velocity distribution of the atomic beam. Note that in the case of diffraction at thin gratings a constant diffraction intensity would be expected in the investigated range of incidence angles. The next curves show the same experiment, but with intensity modulation frequencies in the range of 25 to 250 kHz in steps of 25 kHz. In contrast to the static case two pronounced side peaks appear in each curve. They are located symmetrically around the central Bragg angle. Their angular separation from the central peak increases linearly with the modulation frequency. The absolute position of the diffracted peaks agrees with the positions expected from Eq. (2) within the 8% uncertainty of our absolute angle calibration. The width of the side peaks broadens with larger angular detuning, because the spatial frequency distribution, $\Delta\omega_{\mathrm{spat}}$, experienced by the atoms on their trajectories through the light crystal broadens due to the longitudinal atomic velocity distribution. This increases the range of incidence angles at which diffraction is possible.

In the next part of the experiment we directly demonstrate the coherent frequency shift of the first order diffracted atoms by interferometric superposition with the transmitted beam. Directly behind the light crystal the two outgoing beams form an atomic interference pattern with the light grating period (see inset of Fig. 4). This density modulation can be probed by a thin absorptive grating with the same periodicity. If the de Broglie frequency of the diffracted atoms is shifted by ω_{mod} the atomic interference pattern continuously drifts in the direction of its grating vector. This will result in a temporally oscillating total atomic transmission through the absorption grating. In our case the thin absorptive grating is realized by a thin standing light wave tuned exactly on resonance with the 801 nm transition of the metastable argon atoms. If this transition is excited, there is a 70% probability for the atoms to relax to the argon ground state which cannot be detected by our channeltron detector.

Figure 4 shows the result of such an experiment. The intensity of the light crystal is modulated with a frequency of $\omega_{\mathrm{mod}} = 2\pi \times 100$ kHz. The mirror angle is adjusted to the dynamic Bragg angle for the 100 kHz modulation.

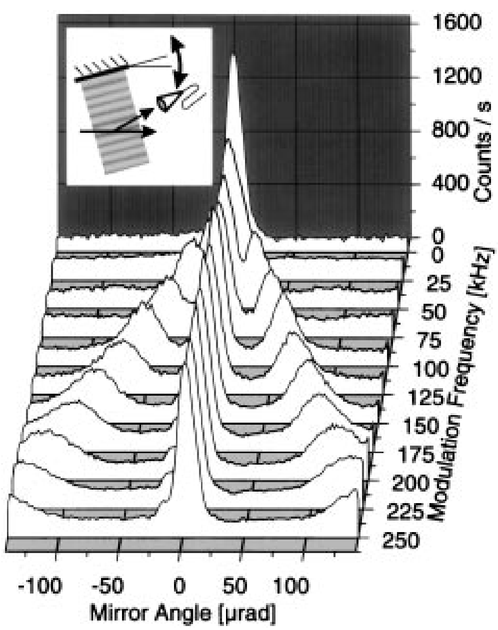

FIG. 3. Diffracted atoms as a function of their incidence angle at the standing light wave (see inset), at different intensity modulation frequencies (0 to 250 in steps of 25 kHz). The detection slit is located at the position of the arrow in Fig. 1, such that only diffracted atoms are registered.

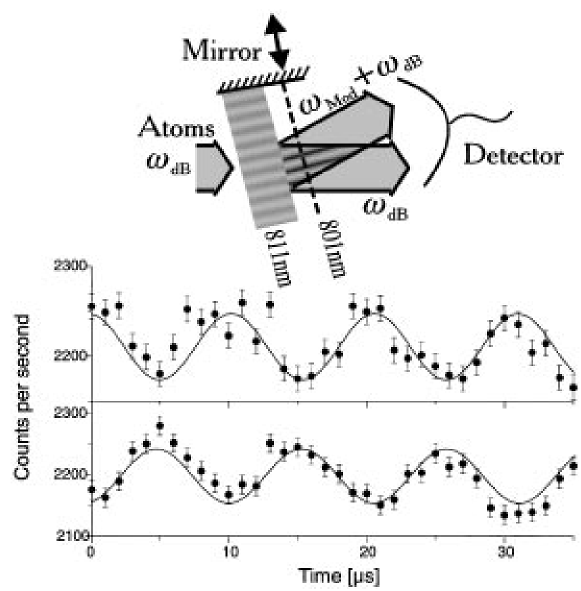

FIG. 4. A thin stationary absorptive grating (801 nm focused standing light wave) probes the traveling atomic interference pattern behind the modulated (100 kHz) 811 nm light crystal. The total atomic transmission is detected as a function of time. A relative phase shift of π between the two light waves is introduced by shifting the common retroreflection mirror by 16.4 μm. This results in a corresponding π phase shift of the atomic transmission oscillations between upper and lower data graphs.

A channeltron detector located directly behind the absorptive grating measures the transmitted atoms as a function of their arrival time, keeping a rigid relation between intensity modulation phase and triggering of each detection scan. The lower curve of Fig. 4 shows the total transmission through the two-grating set. As expected, the transmission oscillates with the light intensity modulation frequency ($2\pi \times 100$ kHz).

In order to exclude the possibility that these transmission oscillations are due to a temporally oscillating but spatially stationary atomic density modulation after the light crystal, we apply a phase shift to the probing grating. In this case, the total transmission oscillation period should also shift by the same phase, which would not happen in the case of a spatially stationary atomic interference pattern. Such a phase shift can be realized using the different grating constants of our 811 nm light crystal and the 801 nm absorptive wave. This leads to a spatial beating period of 33 μm. By shifting the common retroreflection mirror by a fraction of this period the relative spatial phase of the two gratings is shifted correspondingly. The top curve of Fig. 4 shows such a measurement with the position of the Bragg mirror shifted by 16.5 μm (one half of the spatial beating period) with respect to the previous experiment. Now, the phase of the atomic transmission shifts by π as expected. Both curves together confirm the existence of a traveling atomic interference pattern behind the light crystal, and thus a coherent energy shift of $\hbar\omega_{\mathrm{mod}}$ between diffracted and transmitted atoms.

In conclusion we demonstrated "dynamic" Bragg diffraction of atomic matter waves at intensity modulated light waves, acting as thick refractive index gratings. The new dynamic Bragg angles arise due to a beating between the externally applied intensity modulation frequency and the frequency with which the atoms pass the intensity maxima of the stationary light crystal. Because of energy and momentum conservation the frequency of the diffracted atoms is shifted by the corresponding intensity modulation frequency. Our setup is an easily realizable coherent frequency shifter for a continuous atomic beam. Such a device acts on matter waves in an analogous way as an acousto-optic modulator acts on photons [15]. Accordingly, it might be called an optical Bragg modulator for matter waves.

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