Invited Paper

Atom waves in crystals made of light

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ABSTRACT

Atoms interacting with standing light waves are a model system for the propagation of waves in static and time varying periodic media. We present here experiments studying the *coherent* motion of atomic deBroglie waves in periodic potentials made from *on* and *off* resonant light. We observe anomalous transmission of atoms through resonant standing light waves and experimentally confirm that atoms fulfilling the Bragg condition form a standing matter wave pattern. We furthermore demonstrate how Bragg diffraction of atomic matter waves at a time-modulated thick standing light wave can be used to coherently shift the deBroglie frequency of the diffracted atoms. Our frequency shifter for atomic matter waves is similar to an acousto-optic frequency shifter for photons.

Keywords: atom optics, atom interferometry, dynamical diffraction, waves in periodic media

1 Introduction

The interaction of waves with periodic media provides a plethora of beautiful coherent wave phenomena[1] which are particularly striking for deBroglie waves of massive particles. Many of these have wide applications in neutron optics, electron optics and solid state physics. Atoms interacting with standing light waves now provide a model system to study some of these phenomena in a clean and controlled way[2] and open up new possibilities in studying propagation in time dependent periodic potentials[3,4]

This analogy is based on the fact that a light field can model a *complex* potential for atoms: The interaction between a light field and a two level atom with an additional decay channel of the excited state to a third non interacting state, can be described by the complex optical potential[5]

$$U(x,y) = \hbar \frac{d^2 E(x,y)^2}{\Delta + i\gamma/2}. \tag{1}$$

Here $E(x,y)$ is the electric field connected to the light, d is the dipole matrix element of the transition, Δ represents the difference between the driving light frequency and the eigenfrequency of the transition, and γ is the loss rate from the excited level to the non interacting state. In matter wave optics any potential is equivalent to an index of refraction $n \simeq 1 - \frac{U}{2E_{kin}}$ for the propagating matter wave (E_{kin} is the kinetic energy of the particle). Hence any light field structure can be regarded as a potential (refractive index structure like a hologram) for atomic deBroglie waves.

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Atoms propagating in light crystals have now some distinct advantages in studying propagation in periodic media:

- Using diffractive optics and holography one can, in principle, build a large variety of different light structures, and therefore many different potentials for the atoms.
- The light intensity and frequency can easily be manipulated using laser technology. One can easily design and change the periodic medium. We may consider (a) very weak, elastic interactions such as those in dynamical diffraction,[6] (b) very strong interactions as in channelling and[7] (c) those interactions which are dominated by dissipative processes using on-resonant light; or any combinations thereof.
- The potential can be changed on a timescale much faster than the spatial evolution of the atomic wave-function in the medium. This allows to study a large variety of phenomena in time dependent quantum mechanics.
- In addition light fields can be easily superposed, and translated within each other. This allows many interesting studies of the propagation of the atomic deBroglie wave inside the light potential

In the following we will give a brief description of our experimental apparatus, turn to recalling the basic regimes of coherent propagation in periodic media and will then describe our first experiments demonstrating some basic phenomena for matter waves propagating in static and dynamic potentials.

2 Experimental setup

Our experiments were performed using a beam of metastable Argon atoms[9] propagating in an atomic beam apparatus designed to resolve the tiny deflection of atoms when diffracted at the periodic potential of a standing light wave ($\vartheta_{diff} \approx 32\,\mu$rad for 800 m/s atoms and $\lambda_{light} = 801\ nm$). A detailed description of our experimental apparatus can be found in a recent review.[10] We give here only a brief overview:

The vacuum envelope of the atomic beam consists of five components arranged in three differentially pumped sections: (1) the source chamber, (2) a first collimator to define a well defined beam, and in (3) the multi-purpose chamber for the atom-light interaction, a second collimator to select one outgoing propagation direction, and the detector. The high angular resolution for transverse deflections (about 7 μrad FWHM) is obtained with the two separate collimation sections, each of them formed by two narrow slits (typically 5 μm or 10 μm wide) separated by about 1 m. Scanning the final slit (10 μm) of the last collimator in front of the channeltron detector also provides the fine ***spatial resolution*** for measuring diffraction patterns. In our collimated atomic beam we detect typically 5000 atoms/sec.

Choosing metastable $^{40}Ar^*$ has many advantages for our experiments. It has a simple but very interesting level scheme (see Fig. 1) which provides us with the required open transitions to realise the complex optical potentials (Eq. 1). Starting from the $1s_5$ metastable state there is a ***closed*** transition ($1s_5 \rightarrow 2p_9$) at 811 nm ($J = 2 \rightarrow J = 3$) and an ***open*** transition ($1s_5 \rightarrow 2p_8$) at 801 nm ($J = 2 \rightarrow J = 2$) where the decay proceeds with 72% to the Ar ground state. Starting from the other metastable state ($1s_3$) there are no closed transitions but the transition ($1s_3 \rightarrow 2p_4$) at 795 nm ($J = 0 \rightarrow J = 1$) can be used again as an open transition with a branching ration of 42% to the Ar ground state. In addition the transition across the $2p_4$ excited state allows coherent transfer between the two metastable states from $1s_5$ to $1s_3$. The transition ($1s_5 \rightarrow 2p_4$) at 715 nm ($J = 2 \rightarrow J = 1$) is very weak and has a probability of only 1.9% to fall back to the $1s_5$ state but 56% probability to decay to the $1s_3$ metastable state or 42% to decay to the ground state via the $1s_2$ state.

In addition the metastable atoms can be easily detected using a channeltron, whereas the ground state Ar atoms remain undetected. Therefore in the open transitions metastable Ar atoms pumped to the ground state and are

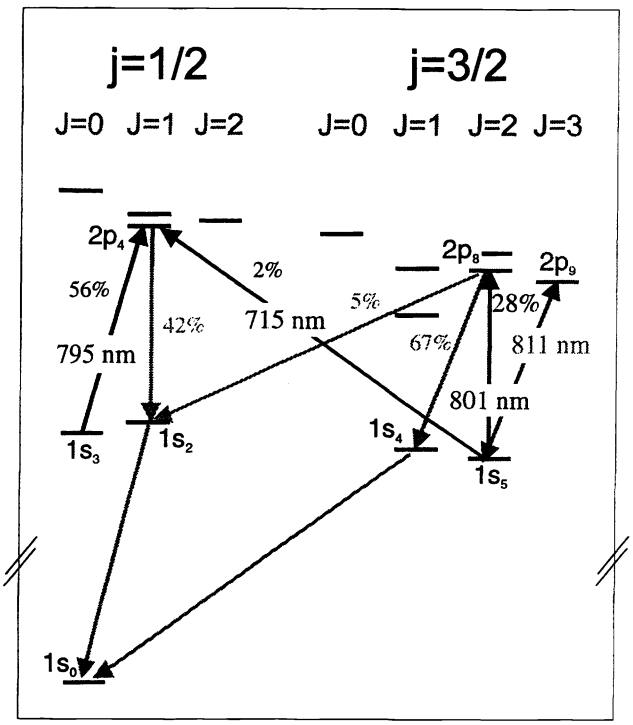

Figure 1: Figure showing the level scheme of metastable Ar, including the branching ratios of the various open decay channels. In our experiments we used the $1s_5$ metastable state and there the *closed* transition ($1s_5 \rightarrow 2p_9$) at 811 nm ($J = 2 \rightarrow J = 3$) and the *open* transition ($1s_5 \rightarrow 2p_8$) at 801 nm ($J = 2 \rightarrow J = 2$).

lost for the detection, they look as being absorbed by the complex potential (Eq. 1). This offers the interesting possibility of realising amplitude gratings (absorptive structures) with light fields.

In the experiments described here we mainly used the 811 *nm* and the 801 *nm* transitions. Varying the detuning of an 801 *nm* standing light wave, we could thus realise real, complex, or pure imaginary potentials for the metastable Argon atoms.

3 Atoms in Light Crystals

Before we proceed to the description of our recent experiments we will present first an overview on the general regimes and parameters relevant for the propagation of atoms in periodic light structures as adapted from crystal physics.

Generally in optics one distinguishes between *thin* and *thick* optical elements depending whether the transverse motion of the wave inside the optical element is significant. A grating with period d_G and thickness D_G can be regarded as *thin* when the separation between different diffracted orders at the back face of the grating is smaller than the grating period. Quantitatively, this implies that $D_G << d_G^2/\lambda_{dB} = \frac{1}{2}L_{Talbot}$ where L_{Talbot} is the Talbot length of near-field diffraction.[11] If the periodic potential extends for longer then a Talbot length

($D_G >> d_G^2/\lambda_{dB}$) then diffraction orders cross the lattice planes and we will call it a crystal. For atomic deBroglie waves passing through such a light crystal one has to consider the interference of all the different scattered waves and a plethora of multi path interference phenomena arise.

If one discusses atomic motion in such a *thick* crystal a second distinction becomes important: whether the motion transverse to the incoming beam direction is free or bound. Depending on these characteristic one can distinguish between two regimes:

- **Quantum Channelling** of particles can be observed if the light shift potential U represented by the planes of the three-dimensional grating is high enough that the particle is confined to one row or plane. This can be formulated either by requiring that there is at least one bound state in a row or plane, or by requesting

$$U >> \frac{\hbar^2 \vec{G}^2}{2M} \tag{2}$$

  where $\vec{G}$ is the reciprocal grating vector and M is the mass of the particle. $\epsilon_{rec} = \hbar^2 \vec{G}^2 \,/\, 2M$ is also referred to as the recoil energy when transferring one momentum $\hbar\vec{G}$ to the particle.

- **Dynamical Diffraction** describes the motion of particles if the potential is much *smaller* than ϵ_{rec}:

$$U << \frac{\hbar^2 \vec{G}^2}{2M} \tag{3}$$

  Then the motion transverse to the lattice planes is quasi free and all the waves scattered at many lattice planes interfere and, typical for dynamical diffraction, ***multi beam*** interference phenomena arise.

Many of the basic phenomena arising in the propagation of waves in periodic media utilise only diffraction at *one* set of crystal planes. A standing light wave can model such a set of crystal planes with adjustable ratio of refractive and absorptive modulation. Therefore we started our first experiments[2,3] with these simple three dimensional structures periodic in one dimension (standing light waves) which we call a *"light crystal"*. Generalisation to light structures periodic in two or three dimensions is then straightforward.

Experimentally the standing light wave was realised by retroreflecting a parallel laser beam from a mirror ($\lambda/10$ flatness) arranged close to the atomic beam inside the vacuum chamber. The surface of the mirror defines a node of the standing light wave and hence the lattice planes of the light crystal which are then parallel to the mirror surface. Rotating the mirror around a vertical axis results in a change of the angle of incidence of the atoms at the light crystal. Measuring the angular dependence[12] of the transmitted or diffracted intensity (a rocking curve) provides an experimentally simple and robust way to study the diffraction processes in the crystal. The mirror could also be translated in a direction perpendicular to the atom beam with a resolution of 0.5 μm.

To build the optical potentials we used diode lasers: One laser diode tuned to the $1s_5 \rightarrow 2p_8$ transition at $801.7\,nm$ provided the light for realisation of the absorption crystal. A second laser diode tuned close to the $1s_5 \rightarrow 2p_9$ transition at $811.8\,nm$ could be used to make a phase crystal. Finally, a laser diode tuned to 795.0 nm ($1s_3 \rightarrow 2p_4$) served to pump the $1s_3$ metastable state to the ground state to reduce our background. The standing light waves where realised by expanding the laser beam to up to 4 cm with a Keplerian telescope.

In the next sections we will give an outlook into this new area of atom optics and atomic interference and present experiments illustrating the fascinating new possibilities arising from dynamical diffraction and multi beam interferences.

4 Amplitude gratings made from *on* resonant light

One straightforward application of the interaction between a light field and a two level atom with an additional decay channel of the excited state to a third non interacting state, is to build amplitude structures with on resonant light.

Let us consider such an atom crossing a thin standing light field tuned *exactly on* resonance. Atoms crossing the standing light wave near the antinodes of the field will scatter many photons and will consequently be pumped to the undetected state. Atoms near the nodes of the light field will have a small probability to scatter light. For sufficiently long interaction times t only atoms crossing near the nodes of the light field will survive. The atomic transmission can therefore (neglecting saturation effects) be written in the form $I = I_0 T$ with $T = \exp(-\kappa \cos(kx)^2)$. For sufficient high light intensities ($\kappa >> 1$ amplitude structures with open slits $< \lambda/10$ can easily be obtained).

To demonstrate that *exactly on* resonant light can be used to build an absorption structure, we measured the total transmission through two such gratings. Translating them with respect to each other allows to estimate the transmission functions of the grating. Figure 2 shows data from such an experiment. The full width at half maximum of the transmission peaks measures $\sim 90\,nm$. Consequently, using *on* resonant light, we could realise an optical mask for neutral atoms with nanometer size, resolution, and accuracy. These masks are a very useful tool to probe small atomic matter wave patterns, as we will show in the following experiments.

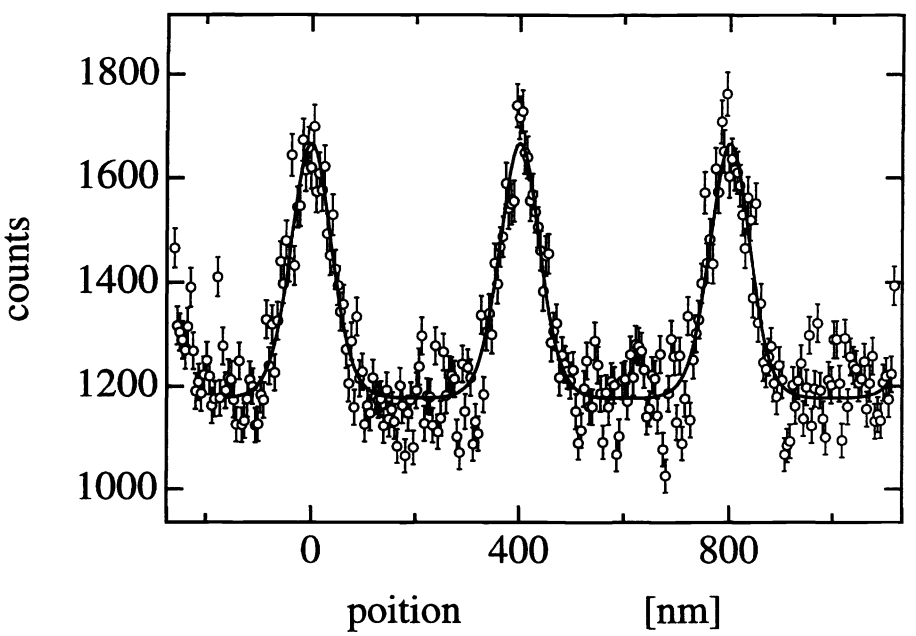

Figure 2: Total transmission through two *on* resonant light gratings as a function of their relative transversal position. The line is a fit with an exponential attenuation law as given in the text.

5 Coherent atomic motion in periodic structures made from *on* and *off* resonant light

In our first set of experiments we studied the coherent motion of atoms in static crystals made from *on* and *off* resonant light.[2] The basic phenomenon for atoms propagating in thick *far off* resonant standing light waves is Bragg scattering which was observed first by Martin et al.[13] and later studied by other groups.[14]

We started our investigations by investigating the propagation of atoms in *on* resonant standing light wave, equivalent to a purely imaginary (absorptive) periodic potential. We experimentally observe that the total number of atoms transmitted through the standing light wave increases if the angle of incidence is the Bragg angle (see Fig. 3). This observation is similar to *anomalous transmission* discovered for X-rays by Borrmann in 1941.[15]

This observed anomalous transmission can be interpreted as Bragg diffraction from a purely imaginary potential. Bragg diffraction implies that inside the crystal, the incident wave gives rise to a coherent diffracted wave, which interferes with the forward propagating wave to form a standing atomic wave field. The difference between these two atomic wave vectors, $\vec{k}_F$ and $\vec{k}_B = \vec{k}_F + \vec{G}$, is equal to the lattice vector $\vec{G}$ which implies a standing atomic wave field with the same periodicity as the standing light wave. The eigenfunctions of the atomic wave field inside the standing light wave can be obtained by applying the principle of extremal interaction[16] analogous to dynamical diffraction of neutrons at perfect crystals. The interaction is maximal if the anti-nodes of the atomic wave field coincide with the planes of maximal light intensity (we will call this state Ψ_{max}) and it is minimal when the anti-nodes of atomic wave fields are at the nodes of the standing light wave (Ψ_{min}). The total atomic wave function inside the crystal is then a superposition of Ψ_{max} and Ψ_{min} satisfying the initial boundary condition.

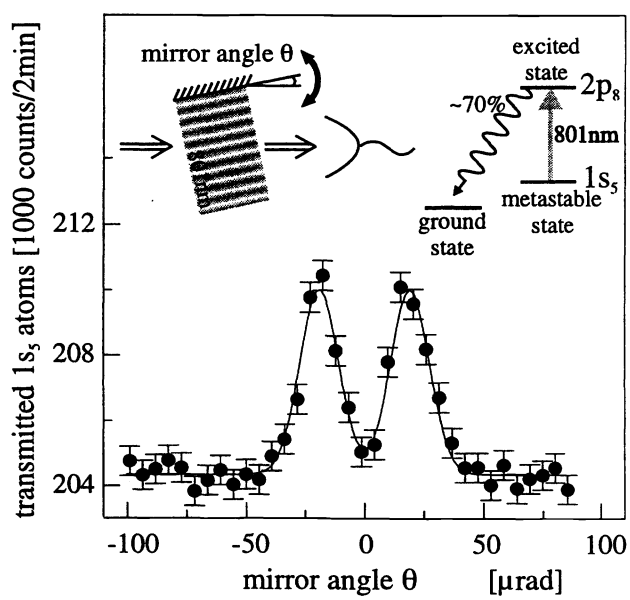

Figure 3: Total intensity of the metastable Ar^* beam after transmission through a standing light wave tuned exactly on resonance to an open transition (see insert) as a function of incidence angle. The transmission increases anomalously for Bragg incidence from either side relative to the planes of the standing light field. The solid line is a fit curve with two Gaussian curves.

Because of the different interaction energies Ψ_{max} and Ψ_{min} accumulate different phase shifts propagating through the crystal, which gives rise to the Pendellösung phenomena of Bragg diffraction.

The above picture leads to a clear intuitive interpretation of the anomalous transmission effect shown in Fig. 3. The rate of depopulation of the metastable state is proportional to the overlap between the atom wave field with the standing light field. It is reduced for Ψ_{min} while it is increased for Ψ_{max} as compared to the average absorption observed for oblique incidence. If the interaction length is sufficiently long, Ψ_{max} is strongly attenuated and the outgoing state is mainly the less attenuated Ψ_{min} resulting in an increase of transmission as compared to an off-Bragg beam interacting with a light crystal of equal length.

We now turn to the question of observing the atomic wave fields inside the light crystal which are a superposition of Ψ_{min} and Ψ_{max}:

The coherence and the relative phase of the two outgoing beams, (the forward and the Bragg diffracted beam) can be measured by recombining them and observing their interference. Experimentally we realised this by placing

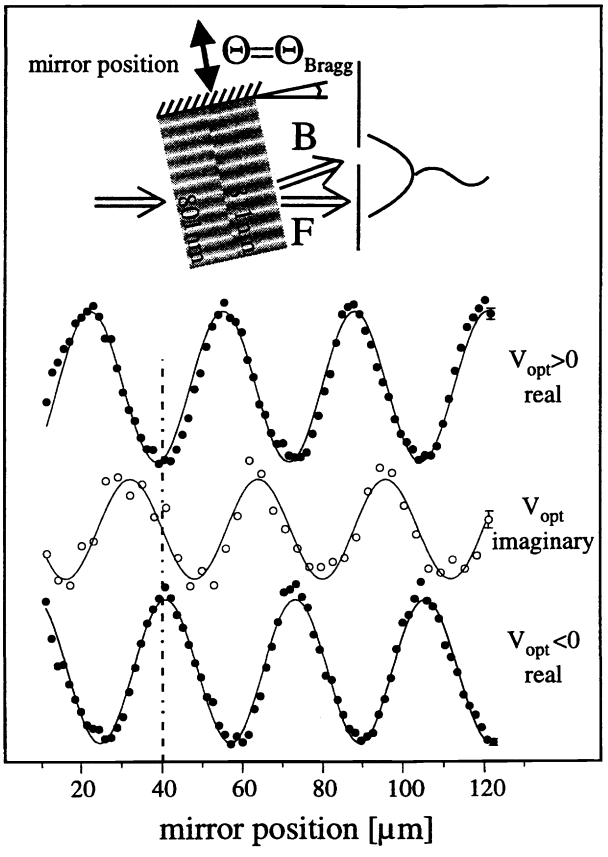

Figure 4: Measurement of the standing atomic wave fields in the light crystal. The anomalously transmitted wave field (middle trace) has its maxima at the nodes of the standing light field. If the 801 nm standing wave is detuned far off resonance, the standing atomic wave is shifted by $\pi/2$ to the left for blue detuning (positive potential) and to the right for red detuning (negative potential).

an additional phase Bragg crystal behind the absorptive respectively phase crystal made with $801\,nm$ light (see Fig. 4). The new phase crystal was realised with a laser tuned far off resonance to the closed transition at $811\,nm$ (red detuned). Since the two standing light waves have different wavelength the relative phase $\Delta\varphi$ between both crystals varies as a function of the distance Δx from the mirror ($\Delta\varphi = 2(\vec{k}_1 - \vec{k}_2)\Delta x$) resulting in a spatial beat period of $32.4\,\mu m$. Moving the mirror one can translate the two crystals relative to each other. The interference is observed as an intensity variation in the two outgoing Bragg diffracted beams with the beating period.

For the absorptive crystal, we expect the atomic wavefield at the exit face to be Ψ_{min}, that is shifted by $\pm\pi$ relative to the light field. For phase crystals, which can be realised by detuning the laser from resonance, the outgoing wave field is a superposition of Ψ_{min} and Ψ_{max}. For Bragg incidence ($\Psi_{in} = e^{\frac{i}{2}\vec{G}\cdot\vec{x}}$) the total wave function inside the crystal is $\Psi = \cos(\frac{1}{2}\vec{G}\cdot\vec{x}) + ie^{i\phi(z)}\sin(\frac{1}{2}\vec{G}\cdot\vec{x})$ which fulfills the boundary condition at the entrance face for $\phi(z=0) = 0$. The resulting total wave function has its maxima at the steepest gradient of the optical potential, shifted by $\pm\pi/2$ relative to the light field.[17] This has to be compared to the case of absorptive crystals where the wave field is shifted by $\pm\pi$ relative to the light field. Equivalently the relative phase between the Bragg and forward diffracted beam in the case of a phase crystal is $\pm\pi/2$ while for the absorption crystal it is π.

The data from an experimental study in this two crystal geometry[2] is shown in Fig. 4. The top (bottom) curve shows the interference pattern for a far blue (red) detuned light crystal made from the $801\,nm$ laser light. We observed the expected π phase shift which arises from the fact that the light shift potential switches sign for red and blue detuning. The curve in the middle was observed for the first crystal exactly *on* resonance at $801\,nm$. First off all the interference confirms the coherence of the observed two beams emerging from the first crystal, even on resonance. Secondly we observe the expected phase shift of $\pi/2$ relative to the far off resonance cases.

In a separate experiment we determined the absolute position of the standing matter wave pattern at the exit of a far off red detuned $811\,nm$ light crystal by masking it by a thin on resonant $801\,nm$ amplitude grating. The gold surface of the retroreflecting mirror defined the nodes of the electric fields for both frequencies. Measuring the transmitted intensity as a function of the distance of the atomic beam from the mirror surface allows then to determine the absolute position of the standing atomic wave field. We found, for incidence angle exactly on Bragg, the maximum of the atomic wave field in the off resonant light crystal to be located at the steepest gradient of the optical potential, in accordance with the above description. The position scale in Fig. 4 reflects this measurement.

6 Atomic motion in time dependent periodic potentials

One advantage of studying the coherent motion of atomic deBroglie waves in light crystals is that the potential can be changed on a timescale much faster than characteristic for spatial evolution of the atomic wavefunction. This allows to study a large variety of time dependent phenomena in quantum theory.

Experiments using time dependent interactions were performed in neutron optics[19] and in recent years using cold Cs atoms.[20] In all these experiments the interaction time was much smaller then the modulation period, this is analogous to the Raman-Nath ("thin-grating") regime in spatial diffraction. In our experiments[3,4] we studied Bragg scattering at a time dependent potential in a regime where the interaction time is much longer than the typical modulation period.

A detailed study of this time-dependent Bragg-scattering is shown in Fig. 5. In these experiments we measure the intensity of the diffracted atoms as a function of the mirror angle (rocking curves). The top graph of the series shows the rocking curve for Bragg scattering off a static (unmodulated) light crystal. Only one peak at the static Bragg angle is observed. The next curves show the same experiment, but with intensity modulation frequencies in the range from $25kHz$ to $250kHz$ in steps of $25kHz$. In contrast to the static case two pronounced side peaks

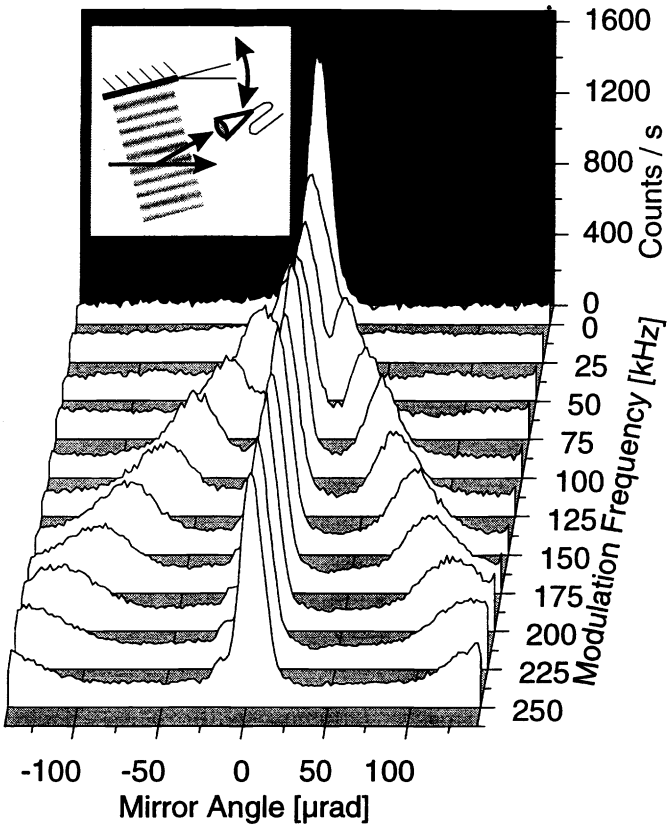

Figure 5: Diffracted atoms as a function of their incidence angle at the amplitude modulated standing light wave (see inset), at different modulation frequencies. The detection slit is located such that only diffracted atoms are registered. The top graph of the series shows the result for an unmodulated light crystal and only one peak at the static Bragg angle is observed. The next curves show the same experiment, but with intensity modulation frequencies in the range from $25kHz$ to $250kHz$ in steps of $25kHz$. 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 deBroglie wave frequency of the atoms in the new Bragg peaks is shifted by $\pm$ the modulation frequency.

appear in each rocking curve, indicating two additional Bragg resonances. They are located symmetrically around the central Bragg angle, and their angular separation from the central peak increases linearly with the modulation frequency.

For an explanation of the observed Bragg scattering at a time dependent potential we first examine the usual case of static Bragg diffraction. In the time independent case Bragg diffraction conserves the kinetic energy of the atoms $|\vec{k}_B| = |\vec{k}_F|$ (elastic scattering) but changes the direction of the atomic momentum by one reciprocal grating vector $\vec{k}_B = \vec{k}_F + \vec{G}$. First order diffraction can occur only at a specific incidence angle, θ_B, which fulfils the Bragg condition: $\sin(\theta_B) = k_L/k_A$.

The Bragg condition can alternatively be interpreted in a different way: Bragg diffraction can be seen, in the rest frame of the incident atom, as a transition in a two state system consisting of a diffracted and an undiffracted state

separated by the energy $\hbar\omega_G = \hbar^2\vec{G}^2/2m$ corresponding to a momentum transfer of $\hbar\vec{G}$. We call ω_G "grating recoil frequency". In static Bragg-diffraction the excitation frequency ω_G in the restframe of the atom is created by the atomic trajectory crossing the spatially modulated light intensity grating ($\omega_{Spat} = 2\pi/\tau = \hbar\vec{G}^2/2m$) which is exactly ω_G.

The new Bragg resonances in the diffraction from an time modulated light crystal can then be interpreted using both viewpoints.

The modulated light field exhibits, besides the carrier frequency ω_c, also sidebands with frequencies $\omega_c \pm \omega_m$ These sidebands in the light field form *moving* light crystals with a velocity of $v = \pm c/2\,\omega_m/\omega_c$. Atoms can now Bragg diffract from these moving crystals.[4] The incident angle for satisfying the Bragg condition is now defined in the moving frame and will be different in the laboratory frame of the experiment, and the energy of the Bragg diffracted beam will be shifted by $\pm\hbar\omega_m$.

Analogously one can explain the appearance of new Bragg resonances in amplitude modulated light crystals by the second viewpoint. For atoms incident at an angle $\theta = \theta_B + \Delta\theta$ detuned from the static Bragg angle the intensity modulation frequency $\omega_{Spat} = 2k_L\frac{\hbar k_A}{m}\tan(\theta_B + \Delta\theta) \approx \omega_{Rec} + 2k_L\frac{\hbar k_A}{m}\Delta\theta$ experienced by the atoms due to their passage through the spatially periodic light grating is *not* the grating recoil frequency required for a Bragg transition. However an additional intensity modulation of the light wave with frequency ω_m results in a sum and a difference frequency $\omega_{Beat} = \omega_m \pm \omega_{Spat}$ experienced by the atoms. Thus, two new resonances appear when ω_{Beat} equals the two-photon recoil frequency required for Bragg diffraction. 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_m.

The absolute position of the diffracted peaks in Fig. 5 agrees, within our measurement accuracy, with the positions expected from the above considerations. The width of the side peaks broadens with larger angular detuning, because the spatial frequency distribution, $\Delta\omega_{Spat}$, 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 our experiment we directly demonstrated the coherent frequency shift of the diffracted atoms by interferometric superposition with the transmitted beam. The two outgoing beams form an atomic interference pattern behind the modulated crystal (see inset of Fig. 6). This density modulation can again be probed by a thin absorptive grating (801 nm on resonant) with the same periodicity. If the de Broglie frequency of the diffracted atoms is shifted by ω_m the atomic interference pattern should travel in the direction of its grating vector. This results in a temporally oscillating total atomic transmission through the absorption grating.

Fig. 6 shows the result of an experiment where the intensity of the light crystal is modulated with a frequency of $\omega_m = 2\pi \times 100kHz$. The mirror angle is adjusted to one of the dynamic Bragg angles for the $100kHz$ modulation. Transmitted atoms are measured 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. 6 shows the total transmission through the two-grating set. As expected, the transmission oscillates with the light intensity modulation frequency ($2\pi \times 100kHz$). The top curve of Fig. 6 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 travelling atomic interference pattern behind the light crystal, and thus a coherent frequency shift of ω_m between diffracted and transmitted atoms.

Our device utilising Bragg diffraction of atoms from a time modulated light crystal acts as a frequency shifter for atomic matter waves similar to an acousto-optic frequency shifter for photons.

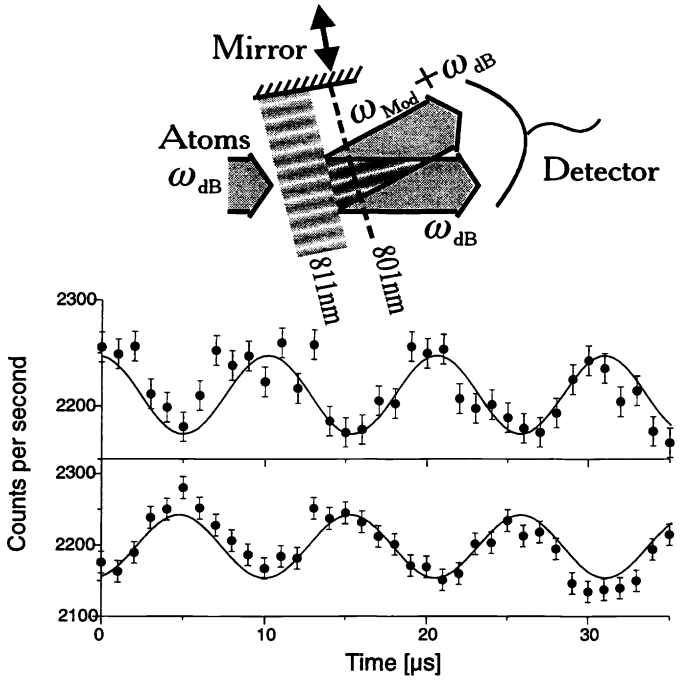

Figure 6: A thin stationary absorptive grating ($801nm$ focused standing light wave) probes the travelling atomic interference pattern behind the modulated ($100kHz$) $811nm$ light crystal. The total atomic transmission is detected as a function of time showing the interference between matter waves of different frequencies. A relative phase shift of π between the two light waves is introduced by shifting the common retro-reflection mirror by 16.4 μm. This results in a corresponding π-phase shift of the atomic transmission oscillations between upper and lower data graphs.

7 Conclusion

Concluding we want to emphasise that the possibility to build complex light potentials of a wide variety leads to a new tool for creating, manipulating and investigating matter wave fields. We expect that the experimental possibilities opened up here will lead to detailed and clean investigations of many wave propagation phenomena in periodic media. This will include model systems for similar effects in other areas of physics.

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8 REFERENCES

[1] J.M. Cowley *Diffraction Physics*, North Holland (1990)

[2] M.K. Oberthaler, R. Abfalterer, S. Bernet, J. Schmiedmayer, A. Zeilinger, Phys.Rev.Lett. **77**, 4980 (1996)

[3] S. Bernet, M.K. Oberthaler, R. Abfalterer, J. Schmiedmayer, A. Zeilinger, Phys.Rev.Lett. **77**, 5160 (1996).

[4] S. Bernet, M. K. Oberthaler, R. Abfalterer, J. Schmiedmayer, and A. Zeilinger, Quantum Semiclass. Opt. **8**, 497 (1996).

[5] D.O. Chudesnikov and V.P. Yakovlev Laser Physics **1**, p. 110 (1991)

[6] B.W. Batterman, H. Cole, Rev. Mod. Phys. **36**, 681 (1964); H. Rauch and D. Petrascheck in *Neutron Diffraction*, p.303, ed. H. Dachs Springer (1978)

[7] D.S. Gemmell, Rev.Mod.Phys. **46**, 129 (1974).

[8] A recent overview on atom optics and interferometry can be found in: *Atom Interferometry*, ed. P.R. Berman, Academic Press (1997)

[9] our experimental apparatus is described in: H. Batelaan, S. Bernet, M.K. Oberthaler, E. Rasel, J. Schmiedmayer, A. Zeilinger, in: *Atom Interferometry* edited by P. R. Berman (Academic Press, Cambridge, MA, 1997) p 85-120.

[10] There are two long lived metastable states in Argon, ^{40}Ar: $[3p^5 4_s]1s_5$ and $[3p^5 4_s]1s_3$ and the lifetime of the metastable state (>> 1 s) is much longer than the flight time of the atoms (<10 ms) and hence can be regarded as a stable state for all our experiments

[11] Philos. Mag. **9**, 401 (1836); L. Rayleigh, Philos. Mag. **11**, 196 (1881); J. Cowley, A. Moodie, Proc. Phys. Soc. B **70**, 486 (1957); **70**, 497 (1957); **70**, 505 (1957).

[12] In our experiments the angular dependence could ne measured with accuracy and reproducibility of $\pm 1 \mu rad$ using a PZT

[13] Bragg scattering of atoms from a far detuned standing light wave was observed by: P.J. Martin, B.G. Oldaker, A.K. Miklich and D.E. Pritchard Phys.Rev.Lett. **60**, p.515 (1988)

[14] D.M. Giltner, R.W. McGowan, Siu Au Lee, Phys. Rev. A **52**, 3966 (1995). S. Dürr, S. Kunze, and G. Rempe, Quantum Semiclass. Opt. **8**, 531 (1996).

[15] G. Borrmann Z. Physik **42**, 157 (1942); anomalous transmission was also observed for neutrons: S. Sh. Shilshtein, V.J. Marichkin, M. Kalanov, V.A. Somenkov, L.A. Sysoev Zh. ETF Pis. Red. **12**, p.80 (1970); and electrons: A. Mazel and R. Ayroles J. Microscopie **7**, p.793 (1968).

[16] M.A. Horne, K.D. Finkelstein, C.G. Shull, A. Zeilinger and H.J. Bernstein in *Matter Wave Interferometry*, p.189, ed. G. Badurek, H. Rauch, A. Zeilinger North Holland (1988)

[17] If the interaction length is N*Pendelösung/2, the maxima are at the negative gradient for N odd, and at the positive gradient for N even.

[18] B.W. Batterman, H. Cole, Rev. Mod. Phys. **36**, 681 (1964).

[19] Neutrons were slowed by diffraction at moving gratings and mirrors: A. Steyerl, W. Drexel, S. S. Malik, and E. Gutsmiedl, Physica B **151**, 36 (1988), and references therein; sent through time-dependent potentials: G. Badurek, H. Rauch, and D. Tuppinger, Phys. Rev. A **34**, 2600 (1986); or deflected by time-dependent mirrors: R. Gaehler, R. Golub, Z. Phys. B **56**, 5 (1984), J. Felber, R. Gähler, C. Rausch, and R. Golub, Phys. Rev. A **53**, 319 (1996).

[20] Recently time dependent experiments have been performed with cold Cs atoms released from a magneto-optical trap by reflecting them from a vibrating mirror: A. Steane, P. Szriftgiser, P. Desibiolles, and J. Dalibard, Phys. Rev. Lett. **74**, 4972 (1995); P. Szriftgiser, D. Guéry-Odelin, M. Arndt, and J. Dalibard, Phys. Rev. Lett. **77**, 4 (1996).