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ATOM WAVES IN STANDING LIGHT WAVES[1]

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Atoms interacting with standing light waves are a model system for the propagation of waves in static and time varying periodic media. Here we present experiments studying the *coherent* motion of atomic de Broglie waves in *static* 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 inside the crystal. By superposition of absorptive and refractive light crystals we can create complex potentials and study Bragg diffraction at these structures. In certain cases the diffraction patterns are asymmetric an example of a violation of Friedel's law. We furthermore demonstrate diffraction of atoms at thin absorptive structures made of light. With these masks for de Broglie waves we can localize atoms to a 1/10 of an optical wavelength.

1. Introduction

The interaction of waves with periodic media provides a plethora of beautiful coherent wave phenomena [1] which are particularly striking for de Broglie 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].

The analogy between photon and matter wave diffraction 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]

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

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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 resonancefrequency of the transition, and γ is the loss rate from the excited level to the non interacting state. In matter wave optics it is easy to change between refraction (real potential) and absorption (imagine potential) just by varying the light frequency.

Atoms propagating in light crystals have 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 channeling and [7] (c) those interactions which are dominated by dissipative processes using on-resonant light.
- By superposing light crystals with different real and imaginary parts, it is possible to create complex potentials, with an arbitrary spatial phase between refraction and absorption.
- The potential can be changed on a timescale much faster than the spatial evolution of the atomic wavefunction in the medium. This allows to study a large variety of phenomena in time dependent quantum mechanics [3].
- In addition light fields can be easily superposed, and translated within each other. This allows many interesting studies of the propagation of the atomic de Broglie wave inside the light potential

In the following we will give a brief description of our experimental apparatus and show first experiments done with thin absorptive masks made of standing light waves to localize atoms. Then we turn to recalling the basic regimes of coherent propagation in periodic media and will describe our first experiments demonstrating some basic phenomena for matter waves propagating in static 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 ($\vartheta_{diff} \approx 32$ μrad 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 chamber of the experiment consists of five components arranged in three differentially pumped sections: (1) the source chamber, (2) a first collimator made with two slits to define the atomic beam, and in (3) the multi-purpose chamber for the atom-light interaction and a third slit in the farfield and the detector. The high transversal collimation of about 7 μrad is obtained with two narrow slits (typically

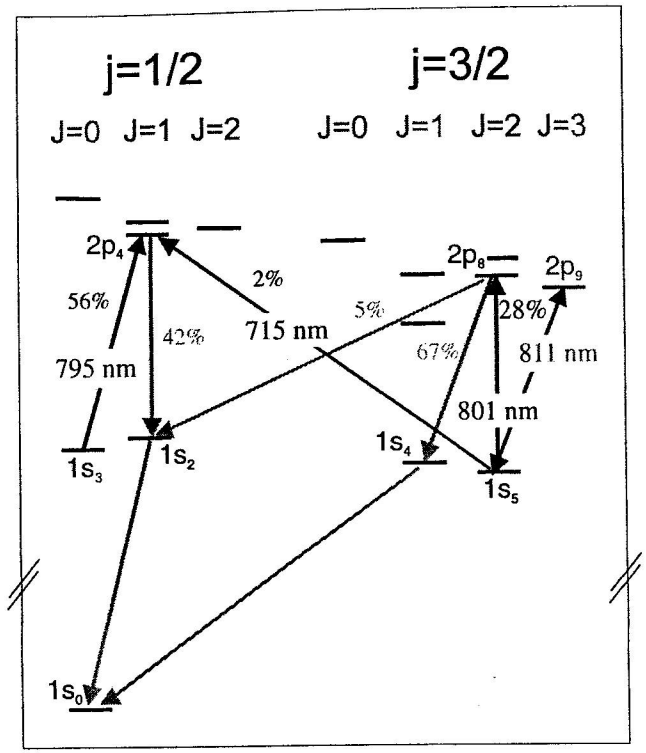

Fig. 1. Showing the level scheme of metastable Ar, including the branching ratios of the various open decay channels. In our experiments we used the $1s_5$ metastable state and there the *closed* transition ($1s_5 \rightarrow 2p_9$) at 811 nm ($J = 2 \rightarrow J = 3$) and the *open* transition ($1s_5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

10 μm and 5 μm wide) separated by about 1.5 m. Scanning the final slit (10 μm) in front of the "channeltron" detector 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 transition to realize 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. This is useful to get rid of the metastable atoms in the $1s_3$ state. In

our experiments this reduces the background, because the gasdischarge produces 15% of the metastable atoms in this 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 are pumped to the ground state and are lost for the detection, they look as being absorbed by the complex potential (Eq. 1). This offers the interesting possibility of realizing amplitude gratings (absorptive structures) with light fields.

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

3. 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 [2, 11].

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

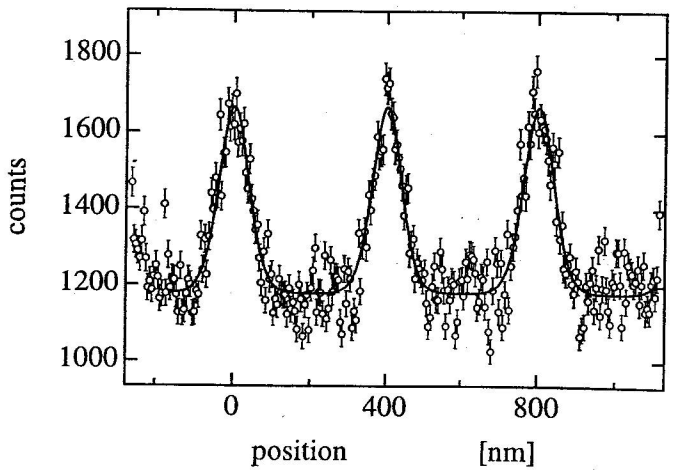

Fig. 2. Total transmission through two successive *on* resonant light gratings as a function of their relative transversal position. The line is a fit with an exponential attenuation law as given in the text.

will survive. The atomic transmission I, can therefore (neglecting saturation effects) be written in the form $I = I_0 T$ with $T = \exp[-\kappa \cos(kx)^2]$. For sufficiently high light intensities ($\kappa \gg 1$) amplitude structures with open slits $< \lambda/10$ can easily be obtained.

To demonstrate that *on* resonant light can be used to build an absorption structure, we measured the total transmission through two such gratings placed directly behind each other. Translating them with respect to each other allows to estimate the transmission functions of the grating. Fig. 2 shows data from such an experiment. The full width at half maximum of the transmission peaks measures $\sim$ 90 nm corresponding to 65 nm behind each single grating (deconvolution). Consequently, using *on* resonant light, we could realize 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.

4. 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 $D_G \ll d_G^2/\lambda_{dB} = \frac{1}{2} L_{Talbot}$ where L_{Talbot} is the Talbot length of near-field diffraction [12]. If the periodic potential extends for longer then a Talbot length ($D_G \gg d_G^2/\lambda_{dB}$) then diffraction orders cross the lattice planes and we will call it a crystal. For atomic de Broglie 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:

- **Dynamical Diffraction** describes the motion of particles if the light shift potential V represented by the planes of the three-dimensional grating is much *smaller* than ϵ_{rec} and the particles transverses the planes:

$$V \ll \frac{\hbar^2 \vec{G}^2}{2M}, \tag{2}$$

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. In this regime 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.

- **Quantum Channelling** of particles can be observed if the potential 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

$$V \gg \frac{\hbar^2 \vec{G}^2}{2M}. \tag{3}$$

Many of the basic phenomena arising in the propagation of waves in periodic media utilize 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"*. Generalization to light structures periodic in two or three dimensions is then straightforward.

Experimentally the standing light wave was realized by retroreflecting a collimated 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 [13] 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 realization 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. We also use a Titanium/Sapphire laser at 811 nm far detuned (> 1 GHz) to create phase crystals. 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 realized 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.

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. [15] and later studied by other groups [16].

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 [17].

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 [18] 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

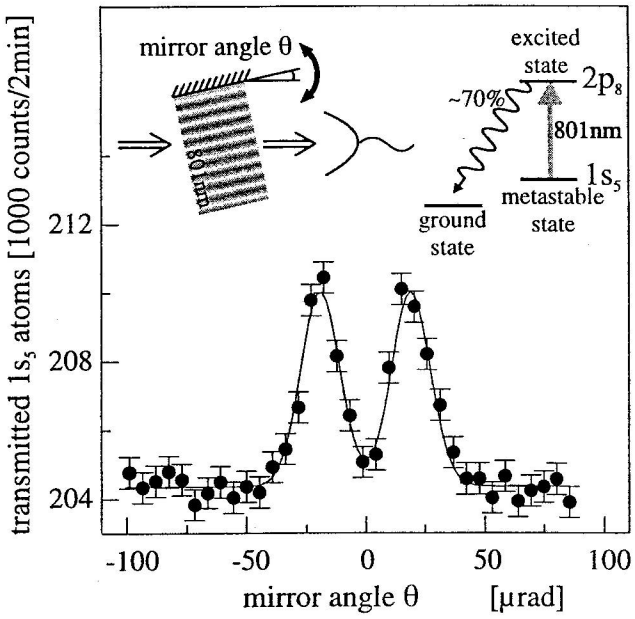

Fig. 3. Total intensity of the metastable Ar^* beam after transmission through a standing light wave tuned exactly on resonance to an open transition (see insert) as a function of incidence angle. The transmission increases anomalously for Bragg incidence from either side relative to the planes of the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

condition. Because of the different interaction energies Ψ_{max} and Ψ_{min} accumulate different phase shifts propagating through a refractive 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 atomic wave field and 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

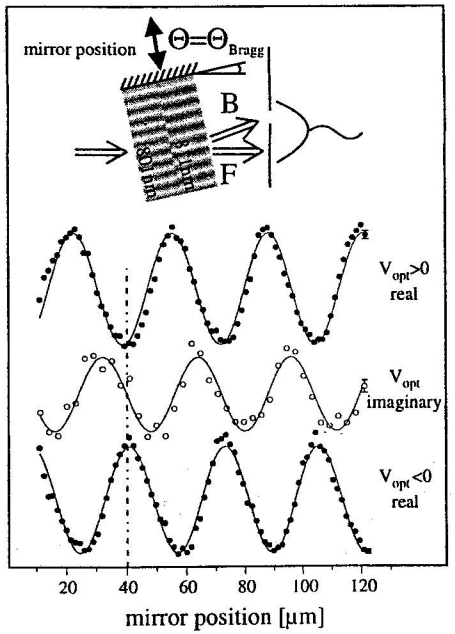

Fig. 4. Measurement of the standing atomic wave fields in the light crystal. The anomalously transmitted wave field (middle trace) has its maxima at the nodes of the standing light field. If the 801 nm standing wave is detuned far off resonance, the standing atomic wave is shifted by $\pi/2$ to the left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

the Bragg diffracted beam) can be measured by recombining them and observing their interference. Experimentally we realized this by placing an additional phase Bragg crystal behind the absorptive or, respectively, phase crystal made with 801 nm light (see Fig. 4). The additional phase crystal was realized with a laser tuned far off resonance to the closed transition at 811 nm (red detuned). Since the two standing light waves have different wavelengthes the relative phase $\Delta\varphi$ between the two 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 μm. 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 realized by detuning the laser from resonance, the outgoing wave field is a superposition of Ψ_{min} and Ψ_{max}. For Bragg incidence ($\Psi_{in} = \exp\frac{i}{2}\vec{G}\cdot\vec{x}$) 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 [19]. 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. Bragg diffraction in general complex potentials - Violation of Friedel's law

Typically diffraction phenomena are invariant under an inversion of the crystal. This fact is generally refered to as Friedel's law [20, 21] and means that there is no difference

in diffracted intensities if the role of incidence and outgoing direction is reversed, even when the elementary cell of the crystal posses no symmetry. The diffraction symmetry can be broken only in cases when the crystal consists of absorptive and refractive index components with a different spatial distribution such that the combined crystal has no center of symmetry [22].

Roughly speaking, the violation of symmetry in diffraction is due to the fact, that two different phase shifts - a *spectrally* induced phase, related to the principles of diffraction at absorptive and refractive structures, and a *spatially* induced phase, related to the position of the crystals, have to be considered. Whereas the *spectrally* induced phase is independent of the sign of the diffraction order, the *spatially* induced phase switches sign in conjugate diffraction orders.

A *spectrally* induced phase shift of $+\pi/2$ or $-\pi/2$ arises (depending on the sign

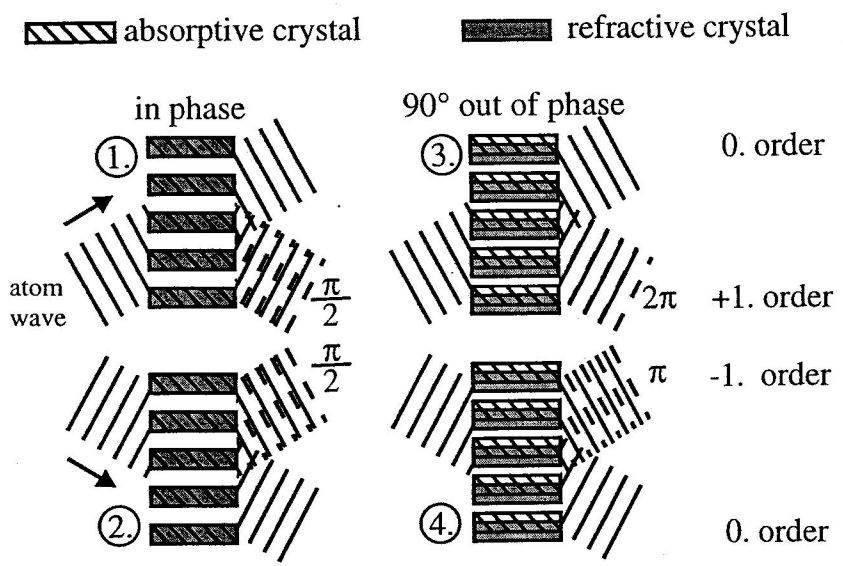

Fig. 5. "Intuitive" picture for the asymmetric diffraction in conjugate Bragg orders: There is a phase difference of $\pi/2$ between diffraction at absorptive and at refractive index potentials. An additional phase difference arises from a spatial displacement of the two gratings, which changes sign in the two conjugate orders. The relative phase of the waves diffracted at the refractive and absorptive index grating is indicated by the phase between the solid and broken line. In the case where the two crystals are spatially in phase (situation 1. and 2.), symmetric diffraction results (indicated by a phase of $\pi/2$ between the solid and the broken line). However, if the crystals are spatially displaced by one quarter of a grating constant, the interference between spectral and spatial phase shifts leads to increased diffraction in one order (situation 3., solid and broken line in phase), and simultaneously to frustrated diffraction in the conjugate order (situation 4., solid and broken line π out of phase).

of the detuning of the refractive index grating) between the matter-wave components diffracted at the absorptive and the refractive index gratings, due to the properties of the complex potential. This is analogous to conventional light wave optics, where also a $\pi/2$-phase difference between diffraction at a refractive index grating and an absorptive grating appears. This phase shift is independent of the sign of the diffraction order (Fig. 5 situation 1. and 2.). The atom intensities in the two Bragg orders is the same, diffraction is symmetric.

However, at the same time a *spatial* phase shift of two matter-wave components diffracted at the two intersecting absorptive and refractive index gratings arises due to the $\pi/2$ spatial phase shift between the two gratings. Thus, it leads to a $+\pi/2$ phase shift in one diffraction order and simultaneously to a $-\pi/2$ phase shift in the conjugated order, due to geometrical reasons.

The combination of *spectrally* and *spatially* induced phases yields a total phase shift between the matter-wave components diffracted at the absorptive and the refractive index gratings of 0 in the one diffraction order (Fig. 5 sitution 3.), and simultaneously of π in the conjugate order (situation 4.). This consequently leads to constructive and destructive interference in the two diffraction orders, respectively. Effectively, the violation of "Friedel's law" is thus due to the different behavior of a *spatially* induced (by a spatial phase shift) and a *spectrally* induced (by switching from an absorptive grating to a refractive index grating) phase shift in conjugate diffraction orders.

For an experimental demonstration [23] we utilize the fact that two intersecting light crystals can be easily obtained by superposing two light frequencies in one Bragg crystal. One of the frequencies is resonant with the open atomic transition at 801 nm, forming an absorptive crystal, the other frequency is detuned from the closed atomic transition at 811 nm, leading to a refractive index crystal. The two different atomic transitions are chosen in order to obtain a spatial beating frequency of about 32.4 μm between the two gratings (similar to the experiment described above). Thus, by shifting the retroreflection mirror in a direction perpendicular to the atomic beam, we can obtain any spatial phase relation between the two crystals, with a periodicity of 32.4 μm.

Fig. 6 shows the result of an experiment where the diffraction efficiency is compared in the two $+1$ and -1 diffraction orders, at three different phases between the two crystals. As expected, maximal asymmetric diffraction is obtained in the case where a spatial phase shift of $\pm\pi/2$ is applied between the two gratings. This means, that in the experiment a high diffraction efficiency was obtained at a mirror angle corresponding to one of the two symmetric Bragg angles, but almost no diffraction was observed at the corresponding conjugate Bragg angle. In contrast, in the cases of a 0 phase shift between the two crystals, the diffraction efficiency in the two conjugate diffraction orders was symmetric. The asymmetric diffraction efficiency in the cases of the $\pm\pi/2$-phase shifts corresponds to a violation of "Friedel's law", which was reported originally for special types of absorptive crystals [21] and, more recently, for conventional holography in frequency selective materials [24]. The fact that "Friedel's law" is always fulfilled in any purely absorptive or purely refractive crystal [21] implies that no pure structure can exist with the same diffraction behavior as our particular combination of absorptive and refractive index gratings. This consequently means that the complete diffraction

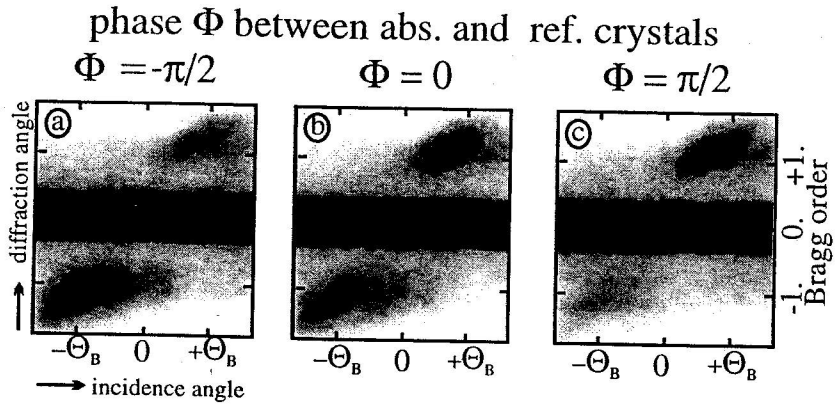

Fig. 6. Scattering of atoms at a superposition of absorptive and refractive light crystals. The atoms are registered as a function of their incidence and their diffraction angles, at 3 different spatial phase positions between the absorptive and the refractive index parts of the light crystal. The 2-dimensional data was recorded by scanning both the angle of the retro-reflection mirror (proportional to the atom's incidence angle) and a 10 μm-slit in front of the extended detector (slit position proportional to the diffraction angle). The black bar in the middle corresponds to transmitted atoms (0. order), whereas the two gray areas on either side of the center represent first order diffracted atoms. If the two crystals are in phase (picture b) the intensities in the two diffraction orders are nearly identical, indicated by the similar gray levels in the side peaks. However, the symmetry is clearly broken in picture (a) and (c), where the crystals are $\pm\pi/2$ out of phase. This asymmetry is a violation of Friedel's law.

behavior of an absorptive (a refractive) grating can never be achieved with any specially designed refractive (absorptive) diffraction structure. The scattering processes at the two types of gratings are fundamentally different.

The results obtained so far demonstrate in great detail equivalent behavior of conventional holography and time-independent matter-wave optics in light crystals. However, in timedepending experiments the equivalence of the Schrödinger-equation with the optical wave equations (in vacuum) does not hold any more and new phenomena may be expected.

7. Conclusion

Concluding we want to emphasize 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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