Absorptive masks of light: A useful tool for spatial probing in atom optics

Claudia Keller,[a] Roland Abfalterer, Stefan Bernet, Markus K. Oberthaler,[b]
Jörg Schmiedmayer, and Anton Zeilinger
Institut für Experimentalphysik, Universität Innsbruck, A-6020 Innsbruck, Austria

(Received 29 May 1998; accepted 28 September 1998)

We demonstrate periodic localization of neutral atoms of better than 65 nm behind amplitude, i.e., absorptive masks made of light. With these masks, produced by a standing on resonant light wave, it is possible to create and to probe spatially well-defined atomic distributions. Applications of such absorptive masks range from atom lithography to fundamental atom optical experiments. As two examples we show how to use these gratings as a tool to measure the evolution of an atomic wave field behind a static Bragg crystal and its dependence on the incidence angle of the atomic beam and how to demonstrate the frequency shift of atoms diffracted at a modulated Bragg crystal in a beating experiment. © *1998 American Vacuum Society.* [S0734-211X(98)18706-1]

I. INTRODUCTION

Efficient methods to prepare and to measure atomic distributions with nanometer resolution are of particular interest in atom optics and for possible applications in science and technology. In atom lithography, for example, the writing of parallel equidistant lines[1–8] with atoms in near resonant light fields is useful to produce very exact scales. A specially useful tool in atom optics are absorptive masks. They can be used to write and to *probe* fine structures. Both have been demonstrated with nanofabricated material masks which were used to deposit nanometer size atomic structures[9] and to read out atomic interference patterns.[10,11]

Here we show how to combine the advantage of absorptive masks with the flexibility of light structures and how they can be used in atom optics.

In order to realize ''absorptive'' light we use the internal structure of our atom and its interaction with the light field.[12] We tune the light frequency to an atomic transition where the spontaneous decay of the excited state proceeds mainly to a different internal state, which is not detected. Atoms in this state can therefore be regarded as being effectively absorbed.[13] Therefore a thin standing light wave tuned on resonance acts as an absorption grating for the atoms. Only atoms passing near the intensity nodes survive in their original state (Fig. 1). The spatial distribution of the atoms behind one such absorptive mask can be detected by probing it with a second identical mask immediately behind the first one. This kind of detection scheme, probing one periodic structure with a second one, results in the well-known Moiré fringes.

In the remainder of the article we will first describe the mechanism to produce absorptive structures of light and then in more detail our experimental realization using a beam of metastable argon atoms. In the first experimental part we will show in detail how to realize periodic localized atomic distributions using on resonant light. In this context we demonstrate the Talbot effect with atomic de Broglie waves describing the evolution of the wave field in the light crystal. In the second part we show that these masks are a useful tool to probe the characteristics of the atomic wave field (amplitude, contrast, and phase) behind a Bragg crystal. These measurements illustrate for the first time the effects predicted from dynamical diffraction theory for a broad range of incidence angles. In the last part we present an experiment where we used the light gratings as a probe to measure a frequency shift of atoms in the kHz range in an interferometric setup. We conclude with an outlook discussing the applications of these structures.

[a]Electronic mail: Claudia.keller@uibk.ac.at
[b]Present address: Clarendon Laboratory, Oxford University, Parks Road, Oxford, United Kingdom.

II. ABSORPTIVE MASKS MADE OF LIGHT

The basic requirement for the generation of absorptive light masks is that the atoms change their internal state after excitation. For sufficiently long interaction times only atoms near the zeros of the light field will remain in their original state (Fig. 1). In our experiments we use a standing light wave realized by retroreflection of a laser beam at a plane mirror. The periodic intensity distribution in the light field is

$$I(x)=\frac{I_0}{2}\,[1-\cos(2kx)], \tag{1}$$

where I_0 is the intensity at the maxima of the standing wave, $k=2\pi/\lambda$ is the wave vector of the incident laser radiation (wavelength of the light λ), and x is the transverse coordinate. The modulus of the grating vector of the light mask corresponds to $2k$ of the light field. In the case of low light intensities[14] we can neglect saturation effects and hence the absorption is proportional to the local light intensity (electric field squared). The atomic transmission through a standing light wave is given by:

$$T=e^{-\kappa\frac{1}{2}[1-\cos(2kx)]}. \tag{2}$$

The absorption κ is proportional to the intensity of the standing light wave [Eq. (1)] [$\kappa\propto\int I_0(z)dz$], where the integration is along the longitudinal direction. Note that the transmission is a nonlinear function of the light intensity. Therefore for sufficiently strong absorption ($\kappa\gg 1$) the transmission evolves into a comb of narrow peaks significantly

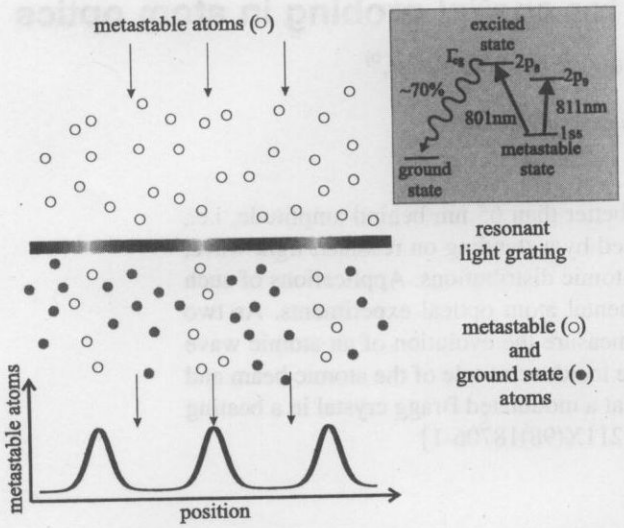

FIG. 1. Absorptive masks of light for metastable argon atoms: Metastable atoms (open cycles) are exited by resonant light and decay spontaneously with a high probability to the undetected ground state (close cycles). Only atoms near the nodes of the standing light wave are detected in localized peaks. Insert shows a level scheme with the used transitions of metastable argon.

smaller than the grating constant $\lambda/2$ (Fig. 2) (see also Ref. 14). As shown in our experiment this can be used to create atomic distributions with subwavelength resolution.

III. EXPERIMENTAL REALIZATION

In our experiment we use a thermal beam of excited (metastable) argon atoms (average velocity of 700 m/s, corresponding to a de Broglie wavelength of $\lambda_{dB} = 14$ pm) which emerge from an effusive argon source.[11] The beam is collimated with a 10 and a 5 μm slit separated by 1.4 m, before entering the interaction region (see inset Fig. 2); after 1.4 m downstream the metastable atoms are detected by a "channeltron."

In the source the atoms are excited by a continuous gas discharge to two metastable states: 85% are in the $1s_5$ state which is used in the experiment and 15% are in the $1s_3$ state which does not interact with our masks and contributes to background. Therefore $1s_3$ atoms are quenched to the ground state by resonant laser light at 795.0 nm. Due to their high internal energy the remaining $1s_5$ metastable atoms can be recorded by our channeltron detector, whereas ground state atoms remain undetected.

For realizing absorption the most important feature of our metastable $1s_5$ atoms is their open transition $1s_5 \rightarrow 2p_8$ at 801.7 nm (linewidth 5.8 MHz). If the atoms are excited at this wavelength they decay spontaneously with a branching ratio of 72% to the ground state (level scheme see inset Fig. 1). The light is produced using a single mode diode laser with grating feedback in Littrow geometry, locked to the 801.7 nm transition using saturation spectroscopy. The linewidth of our laser light (<1 MHz) is much smaller than the atomic linewidth. The absorptive gratings are realized by retroreflection of the 801.7 nm laser beam (focused to a ribbon shape of approximately 3 cm height and 150 μm thickness) on a gold mirror.

The number of atoms in the collimated beam is about 10 000 s^{-1}. In a typical experimental situation one absorptive grating absorbs about 90% of the incident atoms. The typical measurement time to record data as in Fig. 2 is about 15 min.

A second important transition from $1s_5 \rightarrow 2p_9$ at 811.7 nm is closed and used to realize refractive index gratings. If the light frequency is off resonant with the atomic transition it acts as a real potential (corresponding to a real refractive index) for the atoms. Therefore it is possible to build refractive optical elements such as Bragg crystals with light. In the experiment the periodic index of refraction for a crystal was realized with a 4 cm long standing light wave retroreflected at the mirror in the vacuum. The intensity was in the range of 10 mW/cm^2 and the detuning from resonance was 1 GHz. The laser light for this transition was produced by a stabilized Titanium: Sapphire laser.

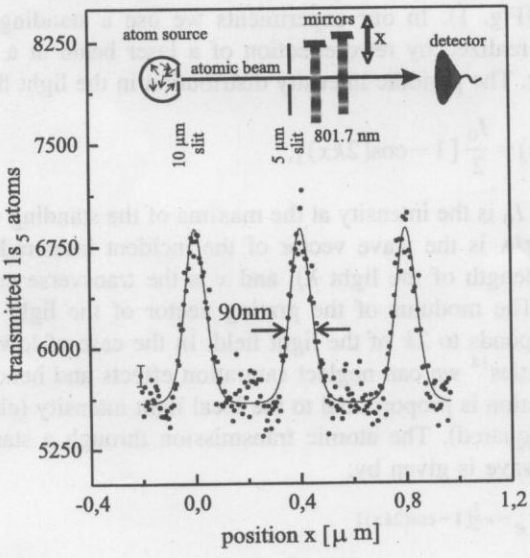

FIG. 2. To demonstrate the localization of the atoms using absorptive light gratings we measured the transmitted atomic intensity through two such gratings as a function of their relative spatial position (experimental setup see inset). The distribution is peaked with a distance of the grating period of 401 nm the measured full width at half maximum (FWHM) of the peaks is 90 nm. This corresponds to an atomic localization of better than 65 nm behind each individual grating.

IV. LOCALIZATION OF ATOMS WITH ABSORPTIVE GRATINGS: TALBOT EFFECT

An absorptive grating transmits atoms only at the nodes of the light field. To demonstrate this localization behind the grating we probe the transmitted atoms with a second mask. The two light gratings for this experiment are realized in front of two gold mirrors (see inset Fig. 2). One of the mirrors is mounted on a flexure stage and can be translated in the direction orthogonal to the mirror surface with nm accuracy. The spacing between the two gratings is adjustable between 3 and 15 mm by shifting one of the laser beams in the direction of the atomic beam. A crucial point in our experi-

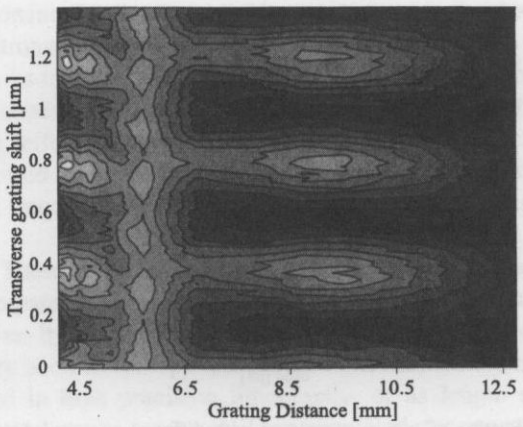

FIG. 3. Behind an absorptive grating the superposition of the different diffraction orders form in the near field a periodic interference patter (Talbot effect). To demonstrate the Talbot effect with de Broglie waves of metastable argon we measured the atomic distribution at several distances, using our absorptive masks. By shifting the absorptive grating transversal with respect to the diffraction grating for a few μm the oscillating behavior is clearly visible. At a distance of 5.8 mm one observes the typical doubling of the spatial period as expected for the Talbot theory (brighter regions correspond to higher atomic densities).

ment is that the two mirrors have to be aligned parallel to each other with better that 10 μrad accuracy, which is done interferometrically.

The result of such an experiment is shown in Fig. 2. The total transmission is plotted as a function of the relative spatial phase between the two successive resonant standing light waves. The data show peaks with a separation of 401 nm. The periodicity corresponds to the grating constant of our standing lightwave which is half the optical wavelength ($\lambda = 801.7$ nm) in our experimental arrangement. The peak width (90 mn) is significantly smaller. A numerical deconvolution implies a spatial localization of the atoms behind each individual grating of better than 65 nm ($\lambda/12$).

The data of Fig. 2 were taken with a relative grating distance of approximately 3 mm. The background of the data is mainly due to 20% of the $1s_5$ ($J=2$) atoms which are originally in the $m=0$ magnetic sublevel and which are not disturbed, since their excitation (with linearly polarized light) to the $2p_8$ ($J=2$) decay channel is dipole forbidden. The light does not influence these atoms, whereas the remaining 80% of the atoms are strongly absorbed (transmission$<10\%$). This background can be removed in further applications by optically pumping the atoms in a defined magnetic sublevel.

As an example of the versatility of our absorptive light masks we investigated the coherent evolution of the atomic wave field behind such a narrow transmission grating as described by near-field Fresnel diffraction. A well-known phenomenon in near-field optics is self-imaging of an absorptive grating, the Talbot effect.[15] For gratings with very narrow slits, images with fractional periods can appear.

Figure 3 shows a series of measurements exploring the near-field atomic density distributions at various locations behind the first mask. We recorded the total transmission through the two masks as a function of their relative spatial phase at various relative distances between the two gratings. The relative spatial phase is varied by shifting one grating with respect to the other transversally by a few μm. The data show clearly that an image with a doubled spatial frequency (period: $\lambda/4$) emerges at a distance of 5.8 mm, as predicted by the Talbot theory. The high collimation (corresponding to a high spatial coherence) of our atomic beam is now essential in order to observe the Talbot fringes. Two effects explain the contrast reduction of the fringes at increasing distance from the light grating. First, the broad velocity distribution of the atomic beam limits the longitudinal coherence length. Second, 28% of the atoms fall back to the $1s_5$ state after spontaneous emission of a photon and contribute to an incoherent background. Nevertheless, our measurement demonstrates both the fact that our masks have a resolution better than light wavelength, and the possibility to produce higher order atomic distributions using near-field diffraction.

V. PHASE MEASUREMENT OF A PERIODIC ATOMIC WAVE FIELD

In diffraction experiments not only thin optical elements such as gratings are important but also thick optical elements such as Bragg crystals. The diffraction at such Bragg crystals shows very different effects. Diffraction becomes only possible for special incidence angles (Bragg angles) and only in one single direction because of energy and momentum conservation. We realize such a structure with a 4 cm long detuned standing light wave at 811.7 nm. If the incidence angle is exactly the Bragg angle the superposition of the two beams (forward beam and diffracted beam) forms a periodic atomic distribution.[16] The period of this wave field is identical to the period of the light field but there is a relative spatial displacement of a quarter of a grating period (corresponding to $\pi/2$). The visibility of the periodic distribution depends on the crystal length and the diffraction efficiency. However this simple picture is only true if the incidence angle is exactly the Bragg angle. For all other incidence angles the behavior is more complicated and has to be calculated in the framework of dynamical diffraction theory. These calculations show that the periodic structure is only visible in a small range around the Bragg angle (acceptance region) and that the relative phase with respect to the light field changes linearly in that area. To demonstrate this behavior in the experiment we placed an absorptive grating immediately behind the Bragg crystal (distance$\leq$1 mm) (setup see inset Fig. 4) and investigate the periodic atomic distribution by the Moiré effect. To probe the wave field we used the fact that the period of the crystal (406 nm) and the grating (400 nm) is slightly different. But with increasing distance from the mirror, the relative phase between the two gratings changes, because of their different periodicities. (The resulting spatial beating period is 34 μm.) Thus moving the mirror away from the thin (5 μm) atomic beam allows us to scan 2π of the relative phase in 34 μm. Therefore the totally transmitted atomic intensity oscillates with this period when translating the common retroreflection mirror (upper part Fig. 4) and contains information about the phase and the

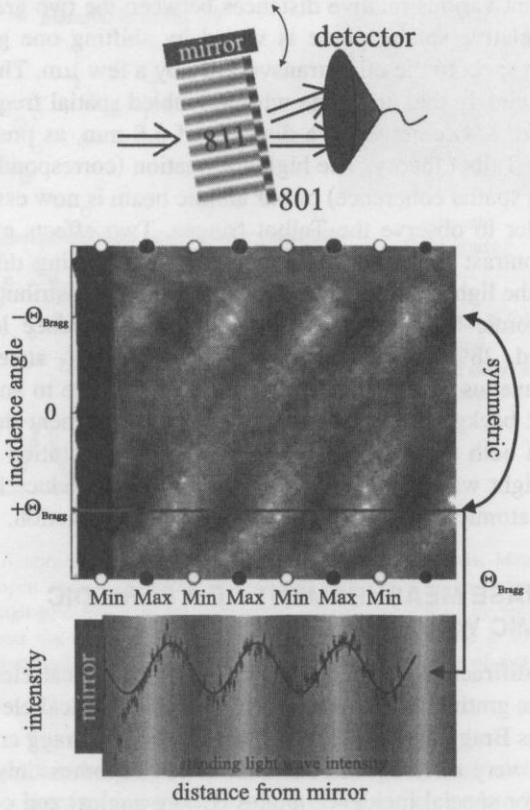

FIG. 4. Measurement of the atomic wave fields behind a static Bragg crystal by placing an absorptive grating right behind the crystal (experimental setup). The measured atomic distribution (middle graph) is plotted in distance form the mirror (horizontal axis) for different incidence angles (vertical axis). In small regions around the Bragg angle the distribution is periodic and the relative phase changes linearly. Exactly on Bragg the intensity distribution of the atoms is plotted relative to the light field in the lower graph. The phase shift of $\pi/2$ between the maxima of the atomic distribution and the intensity in the light field is clearly visible.

amplitude of the standing atomic wave field. The measured data for different incidence angles from $-2\theta_{Bragg}$ to $+2\theta_{Bragg}$ show for the first time the predicted characteristics in detail. The symmetry at the positive and negative Bragg angle is nicely visible. In addition the edge of the retroreflection gold mirror defines the zero point were the two light gratings are in phase. Since the first transmission minimum is displaced from this position by 1/4 of the beating period, we measured a relative phase of $\pi/2$ between the light crystal and the atomic intensity distribution (lower part Fig. 4) at Bragg incidence.

The experiment is an example of the wide range of applications in static measurements with absorptive gratings. One big advantage of the absorptive masks made of light is that they even can measure the atomic localization inside a light crystal which can be important for the imaging properties of optical elements used in atom lithography.

VI. MEASURING THE FREQUENCY SHIFT OF ATOMS WITH ABSORPTIVE GRATINGS

Here we show an applications of absorptive gratings to measure the beating between two coherent matter waves of different energy.

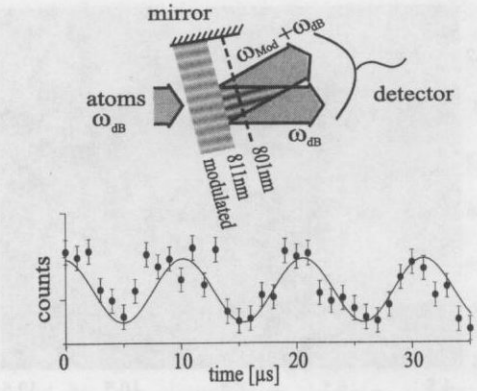

FIG. 5. Beating of two matter waves with different energies: Atoms diffracted at an intensity modulated Bragg crystal of light are frequency shifted (analog to an AOM for light). The superposition of the forward and the Bragg diffracted atoms build an atomic wave field which moves in the direction of the grating vector. To probe the frequency shift we place an absorptive grating in the interference pattern and measure the time dependence of the integral transmitted intensity (setup see inset). Measured oscillations confirm that the frequency of the diffracted atoms is shifted with respect to the transmitted atoms.

Investigating the diffraction of atoms at intensity modulated Bragg crystals the experiments show that new Bragg angles arise. The atoms diffracted at the new incidence angles are frequency shifted by the modulation frequency.[17] The effect is analog to an acusto optical modulator (AOM) for light. To demonstrate this frequency shift of the first order diffracted atoms we again use the interferometric superposition of the diffracted and the transmitted beam. Directly behind the light crystal the two outgoing beams form an atomic interference pattern with the period of the light grating (see inset of Fig. 5). Since 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 results in a temporally oscillating total atomic transmission through an absorptive grating located directly behind the Bragg crystal. In our case the thin absorptive grating is again realized by a thin standing light wave tuned exactly on resonance with the 801 nm transition.

Figure 5 shows the result of such an experiment. The intensity of the light crystal is modulated with a frequency of $\omega_{Mod}=2\pi\times 100$ kHz. The mirror angle is adjusted to the dynamic Bragg angle for the 100 kHz modulation. 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 (setup see Fig. 5). As expected, the transmission oscillates with the light intensity modulation frequency ($2\pi\times 100$ kHz). With this experiment we could directly demonstrate the frequency shift of the diffracted atoms at an intensity modulated crystal.

VII. CONCLUSION AND OUTLOOK

In conclusion, we have realized an optical mask for neutral atoms with nanometer spatial resolution by employing a

resonant standing light field acting on a two-level atom with a strong leak channel to an undetected state. We used our masks to define a narrow atomic distribution and to measure its coherent evolution after the grating in the near field (Talbot effect). To demonstrate the broad applications we showed how to probe periodic wave fields and we confirmed the frequency shifts of atoms diffracted at a modulated crystal.

These masks made from light have many advantages as compared to material masks: their spatial dimensions are given by the optical wavelength, which can be determined very accurately. Applications of light masks may be considered in high precision lithography, or as length standards. Optical masks can be easily manipulated, for example; translated, varied, or switched at short time scales. The shape of the masks can be designed using coherent (i.e., holography) or incoherent methods.[18] An interesting possibility arises because one can readily combine and superpose these masks with other atom optical elements made from light or even material structures.[19] For technical applications it is necessary to develop a source of metastable atoms with a higher flux, especially to illuminate a large area, e.g., on a waver. Using an atom with a higher efficiency of excitation to the metastable state, like neon, could gain a huge factor in atomic flux. We expect that these absorptive light masks will have many applications in atom optics and in atomic lithography.

ACKNOWLEDGMENTS

This work was supported by the Austrian Science Foundation (FWF) Project No. S06504 and by the European Union TMR Grant No. ERB FMRX-CT96-0002. One of the authors (A.Z.) acknowledges support by the U.S. National Science Foundation Grant No. PHY 97-22614.

[1]G. Timp, R. E. Behringer, D. M. Tennant, J. E. Cunningham, M. Prentiss, and K. K. Berggren, Phys. Rev. Lett. **69**, 1636 (1992).

[2]R. E. Behringer, V. Natarajan, and G. Timp, Appl. Phys. Lett. **68**, 1034 (1996).

[3]J. J. McClelland, R. E. Scholten, E. C. Palm, and R. J. Celotta, Science **262**, 877 (1993).

[4]R. Gupta, J. J. McClelland, Z. J. Jabbour, and R. J. Celotta, Appl. Phys. Lett. **67**, 1378 (1995).

[5]R. Gupta, J. J. McClelland, P. Marte, and R. J. Celotta, Phys. Rev. Lett. **76**, 4689 (1996).

[6]R. W. McGowan, D. M. Giltner, and S. A. Lee, Opt. Lett. **20**, 2535 (1995).

[7]M. Kreis, F. Lison, D. Haubrich, D. Meschede, S. Nowak, T. Pfau, and J. Mlynek, Appl. Phys. B: Laser Optics **63**, 649 (1996).

[8]K. S. Johnson, J. H. Thywissen, N. H. Dekker, K. K. Berggren, A. P. Chu, R. Younkin, and M. Prentiss, Science **280**, 1583 (1998).

[9]K. S. Johnson *et al.*, Appl. Phys. Lett. **69**, 2773 (1996).

[10]D. W. Keith, C. R. Ekstrom, Q. A. Turchette, and D. E. Pritchard, Phys. Rev. Lett. **66**, 2693 (1991).

[11]A good overview on atom interferometry and atom optics is given in: *Atom Interferometry*, edited by P. R. Berman (Academic, New York, 1997).

[12]R. Abfalterer, C. Keller, S. Bernet, M. K. Oberthaler, J. Schmiedmayer, and A. Zeilinger, Phys. Rev. A **56**, R4365 (1997).

[13]This optical pumping to an undetected state is a dissipative process, equivalent to absorption.

[14]A. P. Chu, K. K. Berggren, K. S. Johnson, and M. G. Prentiss, Quantum Semiclassic. Opt. **8**, 521 (1996).

[15]H. F. Talbot, Philos. Mag. **9**, 401 (1836); L. Rayleigh, *ibid.* **11**, 196 (1981); J. Cowley and A. Moodie, Proc. Phys. Soc. London, Sect. B **70**, 486 (1957); **70**, 497 (1957); **70**, 505 (1957); The Talbot effect was demonstrated for atoms by: J. F. Clauser and S. Li, Phys. Rev. A **49**, R2213 (1994); M. S. Chapman *et al.*, *ibid.* **51**, R14 (1995).

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

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

[18]S. Bernet, R. Abfalterer, C. Keller, M. K. Oberthaler, J. Schmiedmayer, and A. Zeilinger, J. Imaging Sci. Technol. **41**, 324 (1997).

[19]J. Fujita, M. Morinaga, T. Kishimoto, M. Yasuda, S. Matusi, and F. Shimizu, Nature (London) **380**, 691 (1996).