Atomic Interference in Grazing Incidence Diffraction from an Evanescent Wave Mirror

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We report an experiment showing that atomic diffraction at grazing incidence from an evanescent wave mirror results from polarization gradients in the evanescent wave which induce transitions among atomic internal states. The resulting grating can produce large angle coherent beam splittings. We also demonstrate atomic interference in the form of a Stückelberg oscillation in the diffraction efficiency which is very sensitive to the atom wall van der Waals potential. [S0031-9007(98)07831-4]

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Diffraction at grazing incidence is an important phenomenon in which large period gratings can be used to deflect short wavelength beams through large angles (Fig. 1a). A striking demonstration of the effect occurs when a laser beam is incident on an ordinary ruler at grazing incidence. This is particularly useful in the field of x-ray optics [1] and neutron optics [2]. Similarly, atomic diffraction from a spatially modulated evanescent wave mirror at grazing incidence has also been under study for some time [3–7]. Following the first observations of this phenomenon [8,9], there has been some debate as to the physical mechanism responsible for diffraction because simple, two level models (which ignore light polarization and internal atomic structure) predict vanishingly small effects [6,7,10] at grazing incidence. This vanishing, due to the slow variation of the reflecting potential in the direction normal to the surface on the scale of the de Broglie wavelength, contrasts to the typical optical case of a hard wall reflection grating and is analogous to the case of a thick grating. Through recent theoretical studies, however, a consensus has emerged that the interpretation of the observations of diffraction at grazing incidence must involve the internal atomic structure and polarization effects in the evanescent wave [11–13].

In this paper, we present the results of an experiment clearly demonstrating this. A simple physical model involving Landau-Zener transitions between ground state sublevels allows us to interpret the behavior of the diffraction efficiency. In particular, we observe Stückelberg oscillations, i.e., an interference between several atomic trajectories in the evanescent wave [11,13]. These oscillations are highly sensitive to the exact potential acting on the atoms and thus constitute a new technique for observing the van der Waals interaction between the atom and the dielectric surface supporting the evanescent wave.

Ordinary, scalar diffraction is the consequence of a spatial modulation of an incident wave front and does not involve internal degrees of freedom, such as polarization or spin. At grazing incidence on a thick grating, diffraction is strongly suppressed because the atomic phase, calculated along a classical trajectory, is averaged out over many grating periods [7,14]. This effect is well known in connection with diffraction from acoustic waves [15]. It can also be interpreted [7,16] as the impossibility of satisfying energy conservation in the time independent reflecting potential $V(x, z) = V_0 \exp(-2\kappa z)[1 + \varepsilon \cos 2k_x x]$, where κ and k_x are the imaginary and real parts of the wave vector of the evanescent wave field. Because of energy conservation, the quantum $\Delta p_x = \pm 2\hbar k_x$ of momentum transfer along x due to diffraction must be accompanied by a momentum change $\Delta p_z \approx \pm 2\hbar k_x \tan i$ along z, where i is the angle of incidence (see Fig. 1a). The maximum normal momentum transfer, however, between the zeroth (specularly reflected) order and the diffracted orders is limited to approximately $\hbar\kappa$ because of the spatial extent κ^{-1} of the potential. At grazing incidence, where $\tan i$ is large, one can satisfy energy conservation only by specular reflection.

To understand how polarization effects and internal structure allow one to overcome this impossibility, we consider an atom with two Zeeman ground states m_1 and m_2 bouncing on an evanescent wave far detuned above a resonance. A strong, TM polarized incident beam produces

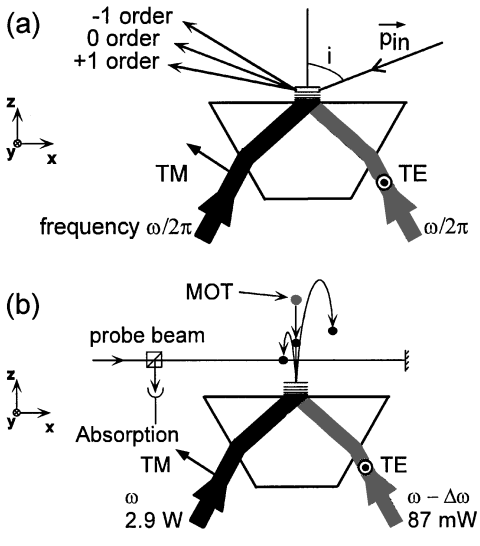

FIG. 1. (a) Schematic of a diffraction experiment at grazing incidence. (b) Schematic of our experiment, which is equivalent to (a) in the reference frame moving horizontally with the atoms.

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an evanescent wave which, for angles not too close to the critical angle, has a predominantly σ^- circular polarization along the y axis (see Fig. 1a). This wave produces different potentials for the two ground states due to the different couplings between the ground and excited states. If one adds a weak TE polarized (π polarized along the y axis) wave propagating in the opposite direction, one can consider the ground state potentials unchanged to first order and treat the effect of the TE wave as a perturbation proportional to $\cos(2k_x x)\exp(-2\kappa z)$ coupling the two internal states. This perturbation also couples momentum states differing by $\pm 2\hbar k_x$ and thus produces diffraction with an internal state change. The energy transfer associated with the momentum change in the normal direction comes from the difference in the light shifts of the two states. The optical analog of this effect consists of a birefringent material the direction of whose optical axis is spatially modulated [17,18]. In the optical analog, diffraction is also accompanied by a polarization change and is thus observed by placing the grating between crossed polarizers. The detection method we describe below is quite analogous.

It is convenient to further analyze this system by shifting the two potential curves by an amount corresponding to the kinetic energy change [6]. The transition between internal states can be understood as a curve crossing (Fig. 2). The atom approaches on one of the two potentials and is "split in two" at the crossing. Its momentum is then reversed by the potential and it reencounters the crossing which again splits the probability amplitude. Which potential curve the atom ends up on, and thus whether or not the atom is diffracted, depends on the splitting amplitude and on the difference in the phases accumulated on the two possible paths. Thus fringes, or Stückelberg oscillations [19], occur in the diffraction probability either as a function of the incident energy or of the position of the crossing.

Our experimental setup is sketched in Fig. 1b. Instead of using a traditional grazing incidence geometry, we allow the atoms to fall from a magneto-optical trap (MOT)

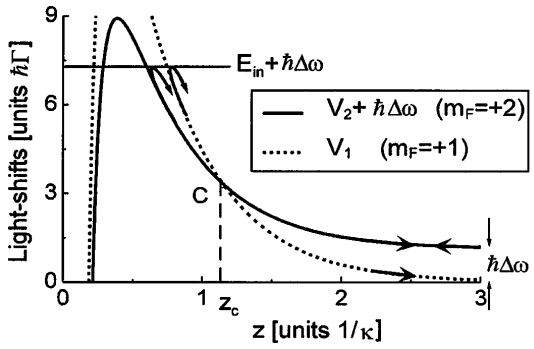

FIG. 2. Potential curves, including the van der Waals force, experienced by the atoms during reflection. The horizontal and vertical scales correspond to our experimental parameters. The atoms arrive on the V_2 potential, pass through the curve crossing twice, and can end up on either V_2 or V_1. Two paths are possible and can interfere producing fringes as a function of the location of the crossing.

onto an evanescent wave mirror at normal incidence and introduce a frequency difference $\Delta\omega$ between the right and left propagating waves to create a moving grating [4,20]. The angle of incidence i in the rest frame of the grating is given by $\tan i = \frac{\Delta\omega}{2k_x v}$, where v is the incident normal atomic velocity. In the lab frame the potential is time dependent [21] and one can think of the level crossing as being between two potentials asymptotically separated by $\hbar\Delta\omega$. Alternatively, one can view the process as a stimulated Raman transition with a Raman shift $\Delta\omega$ [13].

We use largely the same setup as described in Ref. [22]. The main differences are as follows. We use a strong TM wave with a detuning of 1.3 GHz to the blue of the D2 resonance of ^{87}Rb and with a power 2.9 W in about 1 mm^2. After total internal reflection the laser beam is frequency shifted by two double-pass acousto-optic modulators to produce a variable frequency difference $\frac{\Delta\omega}{2\pi}$ between 6 and 22 MHz. Its polarization is also rotated to TE before being sent back into the prism in the direction opposite to the TM beam. The evanescent wave parameters are $\kappa = 1.12k$, $k_x = 1.50k$, where k is the magnitude of the vacuum wave vector of the laser. The MOT is located 17.9 mm above the prism. We optically pump the atoms into one of the extreme m_F states of the $F_g = 2$ manifold. The optical pumping is performed by a circularly polarized and retroreflected laser tuned to the $F_g = 2 \rightarrow F_e = 2$ transition in the presence of a 300 mG guiding field. Because of our optical access, the pumping laser propagates at 45° to the y axis, so that we must adiabatically turn the atom polarization after pumping by varying the guiding field direction on a time scale of about 10 ms. We estimate that more than 93% of the atoms are pumped into the desired m_F level. We detect the atoms using a retroreflected probe laser, with a 1×20 mm^2 cross section, placed 9.6 mm under the trap. We monitor the absorption of the probe as the atoms fall through it after the first bounce on the mirror. Given the initial temperature of the MOT and the temporal duration of the mirror, our time-of-flight resolution is about 10 ms (FWHM).

Typical time-of-flight data are shown in Fig. 3. Several qualitative features are apparent which confirm our model. First, the role of the internal states of the atom is evident. In our case in which the negative m_F states are more strongly shifted than the positive m_F states, an atom pumped into $m_F = -(+)2$ can be diffracted only into positive (negative) orders. Also, one sees in the figure that no more than four diffraction orders can be populated owing to the number of possible m_F changing transitions. Second, we have confirmed that the wrong sign of $\Delta\omega$ results in suppressed diffraction. For a σ^- polarized evanescent wave, our model predicts no diffraction at all because the σ^-/π Raman transition between the two states is always far off resonance if $\Delta\omega$ is negative. However, there remains a 12% residual σ^+ field amplitude so the $m_F = 2$ and $m_F = 1$ states are weakly coupled by a resonant σ^+/π transition. Thus a weak diffraction is still observed. Third, we have verified that no diffraction

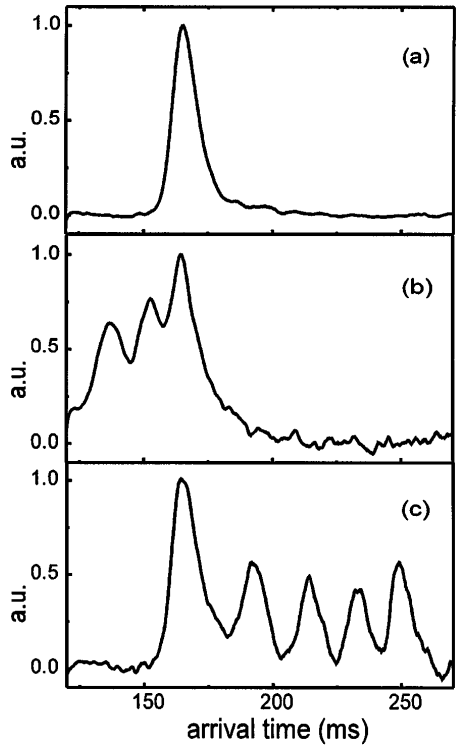

FIG. 3. Time-of-flight spectra for various experimental conditions. (a) No TE beam present. Atoms polarized in $m_F = +2$ reflect specularly from the mirror producing a single peak. (b) TE to TM intensity ratio 0.026, $\Delta\omega = 7$ MHz. Atoms polarized in $m_F = -2$ can be diffracted only into positive orders producing several peaks arriving earlier than the specular peak. (c) TE to TM ratio 0.026, $\Delta\omega = 16$ MHz. Atoms polarized in $m_F = +2$ can diffract only into negative orders during the bounce. All m_F levels are populated after diffraction.

takes place if both laser beams are polarized TM. In this case there is no coupling term between the internal states or different diffraction orders [23]. This situation thus corresponds to scalar diffraction at grazing incidence and thus is highly suppressed. Finally, we have verified that the separations of the peaks in the spectra correspond to energy transfers of integral multiples of $\hbar\Delta\omega$.

We have analyzed the diffraction probability P as a function of $\Delta\omega$ in the regime of low TE beam intensity, when only a single diffraction order is significantly populated. This simplifies the analysis since it should permit a comparison to the two level model discussed in Ref. [13]. To extract P from the time-of-flight data, we normalize the height of the central peak to that of a spectrum with no diffraction (TE intensity zero) and subtract the two spectra. We then fit the remaining peak by a Gaussian curve. We use the area of the fitted peak as a measure of the number of diffracted atoms and the total area of the spectrum as a measure of the total number of reflected atoms. Their ratio gives the experimental value of the diffraction probability. Figure 4 shows a plot of P vs $\Delta\omega$ with evident oscillations.

To compare the data to our model, we perform a calculation as in Ref. [13]. If one ignores the van der Waals

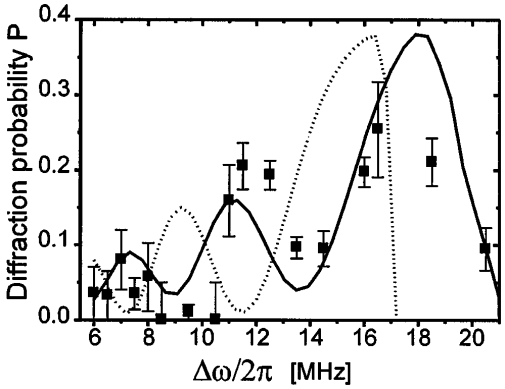

FIG. 4. Diffraction probability P vs $\Delta\omega$ in the low TE intensity (perturbative) regime. Error bars are rough visual estimates from the time-of-flight spectra. The solid curve is a prediction based on the Landau-Zener model including the van der Waals potential. The dotted line is the same calculation but neglecting the van der Waals potential.

potential it is possible to derive an analytic expression for $P(\Delta\omega)$ using the Landau-Zener formula and a Jeffreys-Wentzel-Kramers-Brillouin treatment of the phase accumulated during propagation on the individual exponential potential curves. The van der Waals potential modifies the potential curves and necessitates a numerical integration of the phase. A direct numerical solution of the Schrödinger equation including two m_F levels confirms this calculation. In addition, the fact that the laser beam is Gaussian means that the effect of the van der Waals potential is not the same at every point of the mirror [22]. Thus, we must perform an average over the mirror to accurately model the effect of the van der Waals potential. Finally, because the MOT has a finite spatial extent, the kinetic energy distribution of the atoms when they hit the mirror has a relative width of about 5%. The phase depends sensitively on the incident energy so that we must average over the initial energy distribution. The result is shown in Fig. 4, where we have rescaled the theoretical curve down by a factor of 2.4 (see below). We also show the theoretical prediction when all parameters are the same including the average over the initial energy distribution but ignoring the van der Waals potential. There is clearly a significant shift in the predicted curve in the presence of the van der Waals force as well as a loss of contrast due to the averaging over the mirror. Equally clearly, the phase of the oscillations fit much better to the van der Waals model.

In spite of the good agreement of the phase, our analysis indicates that the diffraction is less efficient than our theory predicts by about a factor of 2.4. One possible explanation for this discrepancy is an error in the TE to TM intensity ratio which would result in the same relative error in the diffraction probability. Our uncertainty in the ratio, however, is estimated to be about 30% (dominated by the uncertainty in the quality of the overlap of the Gaussian TE and TM beams). Another possible explanation may be the effect of spontaneous emission. The

calculated spontaneous emission probability per bounce is about 60% when one includes the modification of the spontaneous emission rate near the dielectric surface [24]. Spontaneous emission can have several effects. It causes an error in our normalization and also modifies the contrast of the interference fringes. Finally, the inclusion of five m_F levels in our theoretical model could modify the predicted diffraction efficiency. A quantitative theoretical investigation of these effects is in progress.

The mechanism we have demonstrated has several interesting ramifications. First, we have demonstrated an efficient large angle atomic beam splitter. The momentum transfer corresponding to $\hbar\Delta\omega$ for $\Delta\omega/2\pi = 18$ MHz is about $20\hbar k$ in our situation. Future applications of the beam splitter include interferometric measurements of gravitational gradients or rotation measurements. The phase of the oscillations themselves amount to an interferometric observation of the van der Waals interaction. Unlike our previous measurements [25], in which we measured only the height of the van der Waals potential at a specific distance, the oscillations depend on the potential along an extended path. Thus, it may be possible to study departures from the z^{-3} law due to retardation corrections as a function of z. This possibility bears some similarity to the situation analyzed in Ref. [26]. Finally, it is important to note that polarization effects such as these may be important in analyzing diffuse reflection of atoms propagating in hollow optical fibers [27]. As discussed in Ref. [13], scattered light can change polarization and lead to inelastic reflection as discussed above. Thus, multilevel atoms may be severely scattered in hollow fibers despite the grazing incidence geometry. On the other hand, knowledge of this mechanism may permit an appropriate choice of parameters (a $J = 0$ atom for example, or appropriate polarizations and atomic beam velocities) to avoid the kind of strong couplings demonstrated here.

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