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New Physics with Evanescent Wave Atomic Mirrors: The van der Waals Force and Atomic Diffraction

N. Westbrook, C. I. Westbrook, A. Landragin, G. Labeyrie, L. Cognet, V. Savalli, G. Horvath, A. Aspect, C. Hendel,[1] K. Moelmer,[2] J.-Y. Courtois,[3] W. D. Phillips,[4] R. Kaiser[5] and V. Bagnato[6]

[1] Institut für Theoretische Physik und Astrophysik, Universität Potsdam, Postfach 60 15 53, 14415 Potsdam, Germany
[2] Institut for Physics and Astronomy, University of Aarhus, 8000 Aarhus C, Denmark
[3] Laboratoire Kastler Brossel, 24 rue Lhomond, 75213 Paris, France
[4] National Institute of Standards and Technology, PHY A167, Gaithersburg MD, 20899 USA
[5] Institut Non Linéaire de Nice, University of Nice-Sophia Antipolis, 06560 Valbonne, France
[6] Institute of Physics of Sao Carlos, University of Sao Paulo, Caixa Postal 369, 13560-970, Sao Carlos, SP Brazil

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Abstract

After a brief introduction to the field of atom optics and to atomic mirrors, we present experimental results obtained in our group during the last two years while studying the reflection of rubidium atoms by an evanescent wave. These involve the first measurement of the van der Waals force between an atom in its ground state and a dielectric wall, as well as the demonstration of a reflection grating for atoms at normal incidence. We also consider the influence of quantum reflection and tunnelling phenomena. Further studies using the atomic mirror as a probe of the van der Waals interaction, and of very small surface roughness are briefly discussed.

1. Introduction

1.1. *Atom optics*

One of the spin-offs of the spectacular advances in trapping and cooling of atoms in the past 15 years has been the development of the field of "atom optics", in which researchers are trying to realize analogs of the many well known devices and techniques of traditional optics, as well as those of neutron and electron optics [1]. The potential applications of atom optics are in part related to the strong coupling of atoms to external fields, leading to improved sensitivity in interferometric measurements: gravitometers, gradiometers and gyroscopes are currently being built and approach already the accuracy of light interferometers [2]. Atom holography [3] and lithography [4] are also generating much interest with their promise of a better resolution due to the small wavelengths of atomic waves.

The de Broglie wavelength of an atom of mass m and velocity v (or temperature T), defined as:

$$\lambda_{dB} = h/mv = h/\sqrt{mk_B T},$$

is a key parameter in atom optics. It can be almost negligible for atoms at room temperature ($\lambda_{dB} \approx 0.02$ nm at $T = 300$ K, $v \approx 500$ m/s), but reaches interesting values around 10 nm for slow atoms falling 15 mm from a trap ($v \approx 0.5$ m/s), and can even go up to the value of the optical wavelength for very cold atoms (typically 50 nK, when the momentum of the atom is equal to that of the photon just absorbed or emitted, $mv = \hbar k$). Laser cooling of atoms thus gives us a knob on the value of our atom optics wavelength.

To manipulate the trajectory of the atoms, the optical components make use of mechanical structures (slits and grids often borrowed from X-ray optics), magnetic fields (using the Zeeman effect) or more often laser beams, that can be tuned close to an atomic resonance to increase the effect on the atoms. The atomic source is either an atomic beam (directly from an oven or slowed down) or a laser cooled atom trap as in the experiments we will describe here. The recent achievement of Bose-Einstein condensation [5] also opens the exciting possibility of using a coherent source analogous to a laser. Indeed interference experiments with Bose condensates have already been realized [6].

1.2. *Atomic mirrors*

Many of the first atom optics experiments concerned interferometry, both demonstrating the observation of fringes and the possibilities of phase shift measurements [7]. The importance of improving the optical elements in these experiments soon appeared, and in particular, our group has been carefully studying the atomic mirror. Everyone knows that in optics the mirror is a widely used component: in telescopes to avoid chromatic aberration; in the Michelson or the Fabry–Perot interferometers, where good quality (i.e. coherent) mirrors are required, either for total or partial reflection; and in laser cavities.

The possibility of a reflection of atoms was first proposed in 1982 using the dipole force exerted by a laser in an evanescent wave [8]. The first experimental demonstrations were performed in 1987 for reflection at grazing incidence [9] and in 1990 for normal incidence [10]. Since then, evanescent wave atomic mirrors have been studied in several groups [11, 12]. In addition, magnetic field gradients were proposed as a candidate to reflect atoms [13], and recent experiments have demonstrated this idea using arrangements of macroscopic magnets [14], as well as audio tape and floppy disks [15].

In our experiments in Orsay, we use an evanescent wave to reflect rubidium atoms. In such a mirror, the reflection is based on the use of the dipole force exerted by a laser beam on a neutral atom when the laser electric field varies in space. This force can be interpreted quantum mechanically as the gradient of the lightshift (or AC stark shift) of the energy levels of the atom in the presence of an electromagnetic field [16]. It can also be understood classically: in the presence of an external electric field $\boldsymbol{E}$, an electric dipole $\boldsymbol{d}$ proportional to the field is induced; this dipole interacts with the field that created it, leading to an interaction energy $-\boldsymbol{d} \cdot \boldsymbol{E}$ that is proportional to the square modulus of the field. In the case of an oscillating field, the same

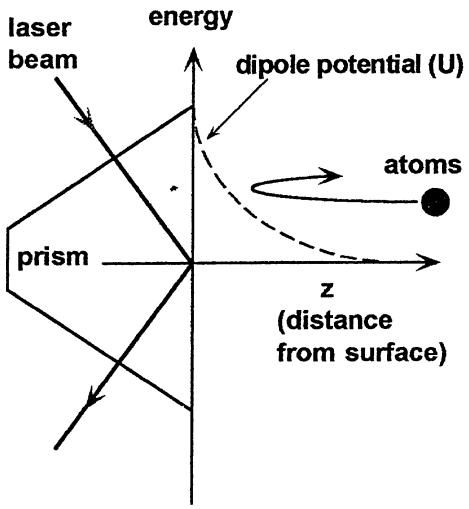

Fig. 1. Principle of an evanescent wave mirror. A laser beam incident from the left is totally internally reflected at a glass-vacuum interface. An evanescent wave is generated on the vacuum side (right). Atoms incident from the right are reflected by a potential barrier which decays exponentially with distance z.

approach is valid at low frequencies where the atomic dipole can follow the oscillations of the field and the dipole will be attracted towards regions of high intensity. The same force is responsible for the possibility of trapping a dielectric sphere at the focus of a laser beam. However, in the case of an atom, narrow resonances appear in the atomic response. Approaching the resonance from below, the interaction energy becomes increasingly negative, due to a larger induced dipole $\boldsymbol{d}$, but it goes to zero exactly on resonance, and becomes positive above resonance because the induced dipole oscillates out of phase with the electric field. Therefore, for a laser tuned above resonance, atoms are repelled from regions of high intensity.

In the case of the evanescent wave atomic mirror, a rapidly varying potential is obtained because of the exponentially decaying electric field at the interface of a prism where a laser beam is totally internally reflected (see Fig. 1). The decay length κ^{-1} of the so-called evanescent wave depends on the angle of incidence of the laser beam, but in our case it is typically of order $\lambda\!\!\!^{-} = \lambda/2\pi(\approx 100\,\text{nm})$ where λ is the wavelength of the laser beam ($\lambda = 780\,\text{nm}$ in our experiments). In the limit of a large detuning and a low saturation, the potential energy increases with the square modulus of the electric field, or its intensity I, and decreases as the detuning Δ, between the frequency of the laser and the atomic resonance, increases:

$$U(z) \propto \frac{1}{\Delta} e^{-2\kappa z}.$$

If the atoms are incident with a kinetic energy lower than the maximum value of this potential (at $z = 0$), they will be reflected. As an example, with a laser beam of $15\,\text{W/cm}^2$, at a detuning $\Delta = 1\,\text{GHz}$ from resonance, rubidium atoms can be reflected if their velocities are lower than 0.5 m/s. Such a large detuning (compared with the natural linewidth of the transition $\Gamma/2\pi = 6\,\text{MHz}$) does not correspond to the maximum value of the potential energy, but we use it in order to reduce spontaneous emission of the atoms while in the evanescent wave. This is important if we wish to obtain a coherent reflection of the atoms on the mirror [10, 12, 17].

2. Measurement of the van der Waals force

From the orders of magnitude given above for the reflection condition for the atoms, it follows that the kinetic energy of the incident atoms will rarely be much smaller than the maximum of the repulsive potential, so that the atoms will bounce at a distance that will be typically of the order of the decay length of the potential, i.e. $\lambda\!\!\!^{-} \approx 100\,\text{nm}$. At such a small distance, the atoms will see not only the evanescent wave but also its support, the dielectric surface. The van der Waals interaction between the atom and the dielectric wall needs then be considered.

2.1. *Van der Waals potential between an atom and a dielectric wall*

The simplest model to understand this interaction is based on the Lennard-Jones calculation [18] of the interaction between a dipole and its image in the dielectric of dielectric constant ε_1. For an atomic dipole with components $\boldsymbol{d}_{\parallel}$ and $\boldsymbol{d}_{\perp}$, parallel and perpendicular to the dielectric interface respectively, the interaction energy takes the form:

$$U_{\text{vdW}} = -[(\varepsilon_1 - 1)/(\varepsilon_1 + 1)][(d_{\parallel}^2 + 2d_{\perp}^2)/64\pi\varepsilon_0]1/z^3$$

as a function of the distance z between the dipole and the interface. In the case of an atom in the ground state, the mean value of the dipole is zero, but its mean square is not, due to quantum fluctuations. There is thus an attractive potential between an atom in its ground state and a dielectric wall. The $1/z^3$ dependence obtained with the simple model is valid only at short distance, i.e. $z \ll \lambda\!\!\!^{-}$, and assuming the dielectric has no resonance near the atomic resonances, so that ε_1 can be taken as a constant. When the distance z increases, retardation effects have to be taken into account, due to the finite propagation time of light between the dipole and its image [19]. At distances $z \gg \lambda\!\!\!^{-}$, the interaction energy then varies as $1/z^4$, which is known as the Casimir-Polder potential.

Compared to the amount of theoretical work on the subject of the van der Waals interaction between an atom and a wall, relatively few experimental measurements have been performed. The attractive potential was first observed in 1975, when Shih and Parsegian measured the deflection of a collimated beam of alkali atoms by a gold plated cylinder [20]. But it was only in the 1990s that more quantitative measurements were performed: a group at Yale measured the van der Waals attraction between sodium atoms and gold surfaces, including the Casimir-Polder effect [21]; and a group at Villetaneuse did spectroscopic measurements of the differential van der Waals effect between ground state and excited state atoms in the case of a vapor of Cs atoms near the dielectric wall of the cell [22]. As we will now show, our method consists of measuring directly the attractive van der Waals force by balancing it with the repulsive dipole force, for rubidium atoms in the ground state reflecting on a dielectric surface.

2.2. *Measuring the van der Waals force in the evanescent wave mirror*

Because of the van der Waals interaction, the potential energy is different from the simple exponential variation shown in Fig. 1. With the addition of the $1/z^3$ attractive potential, the total potential is shown in Fig. 2 for param-

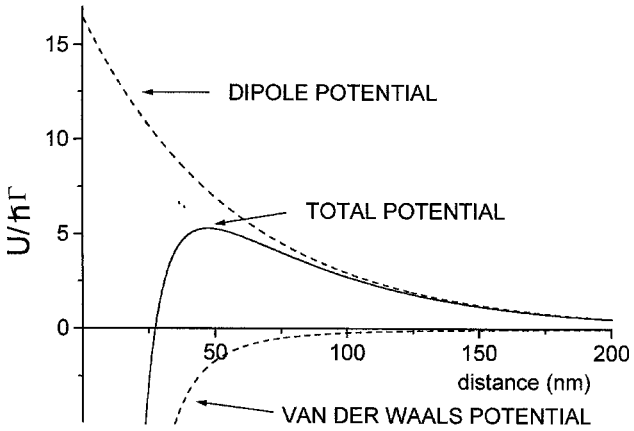

Fig. 2. Potentials seen by atoms as a function of distance from the dielectric interface. The energy units are $\hbar$ times the natural linewidth Γ of Rb ($2\pi \times 6$ MHz). The upper dashed curve is due to the laser dipole potential as shown in Fig. 1. The lower dashed curve is due to the van der Waals interaction. The solid curve shows the sum of these two potentials.

eters close to our experimental situation. The new potential differs significantly from the dipole potential alone, especially for distances of order or smaller than λ. An important modification is that the maximum value of the potential has been reduced by a factor of 3 in our experiment. We could detect this reduction by measuring the reflection threshold as a function of the kinetic energy of the atoms. In our experiment, it is more convenient to keep the kinetic energy of the atoms constant and vary the height of the total potential by varying the height of the dipole potential. This is done by changing the intensity or the detuning of the laser beam. We thus adjust the dipole force to balance the attraction of the van der Waals force.

2.3. *Experiment*

The experimental setup is shown in Fig. 3. Cold atoms are released from a magneto-optical trap, 15 mm above the horizontal surface of a prism. A laser beam from a titanium sapphire laser is totally internally reflected inside this prism, creating an evanescent wave in the vacuum above the surface. After bouncing, the atoms are detected when they cross a probe laser beam placed between the trap and the mirror. The number of atoms crossing the probe beam and the time of their passage are obtained by monitoring the absorption of the probe beam with a photodiode. Figure 4 shows an example of an absorption signal as a function of time, in a case when the probe beam was present from the time of release. It shows peaks when the atoms first fall down from the trap, then bounce back up and fall back down. In our measurements we must be careful to avoid perturbing the trajectory of the atoms with the probe. Therefore, the probe beam is retroreflected and is only turned on after the bounce so as to detect the atoms after reflection. The height of the absorption peak then tells us about the number of atoms that are reflected.

Figure 5 shows the number of reflected atoms as a function of the ratio I/Δ (the intensity over the detuning), i.e. as a function of the height of the dipole potential. A threshold for reflection appears clearly. If the intensity profile of the laser beam were flat, the number of reflected atoms above the threshold would increase immediately to 100%. The logarithmic increase shown in the figure is due to the Gaussian shape of the intensity profile [23]. The value of the threshold can then be compared with the theoretical predictions, shown as arrows on Fig. 5. When taking into account only the dipole potential (arrow "dipole"), the threshold is expected to be at lower intensity, since there is no need to fight against an attractive force. The measured threshold agrees within our experimental uncertainties with the theoretical predictions including the van der Waals interaction (arrows "Lennard Jones" and "QED"). The "QED" prediction for the threshold takes into account the retardation effects mentioned earlier: the finite propagation time induces a phase lag between the dipole and the field of its image, reducing the van der Waals interaction and thus the

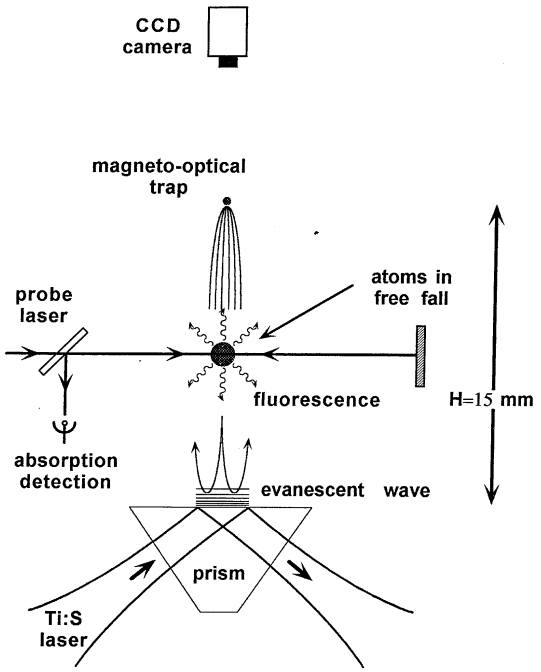

Fig. 3. Schematic diagram of the experimental apparatus. Atoms released from a magneto-optical trap fall approximately 15 mm onto the prism supporting the evanescent wave. As they pass through the sheet-like near-resonant probe laser beam, they scatter light which is detected either by the CCD camera above or by monitoring the absorption of the probe beam.

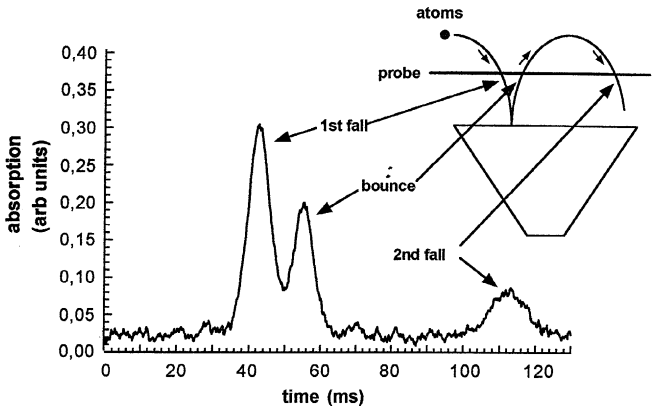

Fig. 4. Typical data recorded by the absorption monitor as a function of time after dropping the atoms. The peaks correspond to the passage of atoms through the probe on the way down before reflection, then up and back down after reflection. The diminishing size of the peaks is due to the transverse loss of atoms at the mirror surface as well as in the probe. The broadening of the last peak is due to heating of the atoms during the previous passages in the probe. In a typical experiment the probe is only turned on during the passage of interest so as to minimize the perturbation of their trajectories.

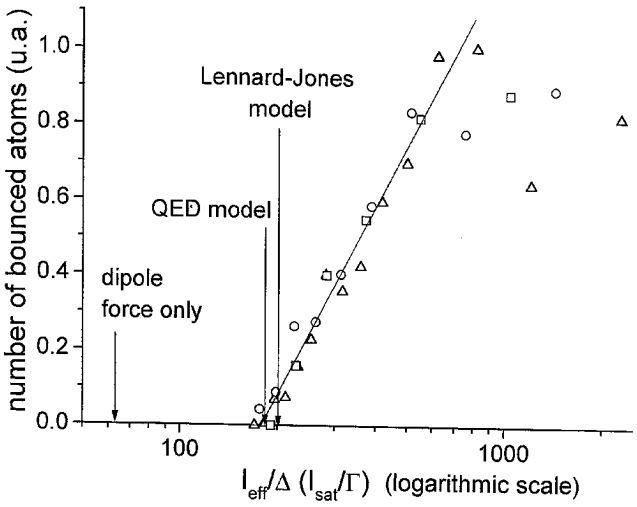

Fig. 5. Number of reflected atoms as a function of intensity divided by detuning in units of I_{sat} (1.6 mW/cm^2 in our case) divided by Γ ($2\pi \times 6$ MHz). The arrows show the thresholds predicted on the basis of different assumptions about the potential (see Section 2.3).

threshold for reflection. This model agrees even better with our data, however the difference is smaller than the experimental uncertainty. More details can be found in Ref. [23].

2.4. *Conclusion and prospects*

An important consequence of this work is that the van der Waals force plays an important role in the functioning of the evanescent wave atomic mirror. We have seen that it reduces the reflection threshold by a factor of 3. The change of shape of the potential is also significant. For example we have shown that it modifies the diffraction efficiencies in the reflection grating for atoms as described below. The interaction between the atom and the dielectric wall also modifies the probability of spontaneous emission [24].

The other interest lies in the measurement of the van der Waals force, performed for the first time for a ground state atom and a dielectric wall. It would be interesting to improve the sensitivity to the retardation effects, and see the transition between the short range interaction in $1/z^3$ and the long range Casimir–Polder $1/z^4$ potential. This would require varying the distance at which the van der Waals force is measured, which corresponds to the position of the maximum of the total potential in our experiment. In fact, our measurement was done for a distance of 47 nm, which is already in the intermediate regime between short and long range.

2.5. *Tunnelling and quantum reflection*

Another interesting experiment would be to look for tunnelling through the barrier and for quantum reflection of atoms with an energy above the barrier height. These effects tend to round off the sharp threshold we mentioned above. There exists a simple analytic formula with which one can estimate the probability of tunnelling or quantum reflection. Using a formula from Ref. [25] one can get an expression for the transmission probability T for an atom to pass a parabolic barrier (i.e. an inverted harmonic oscillator). One finds:

$$T = \frac{1}{1 + e^{(-2\pi E/\hbar\Omega)}}$$

where E is the difference between the atom's energy and the potential barrier height. A negative value of E corresponds to a particle whose energy is below the barrier height and which, classically, would be reflected from the barrier with unit probability. Here Ω is the oscillation frequency that the atom would have if the harmonic oscillator potential were *not* inverted, and thus parameterizes the curvature C at the top of the potential barrier ($\Omega^2 = C/m$).

By expanding the real potential shown in Fig. 2 near its maximum we can find the curvature to use in the above equation. The resulting transmission probability agrees extremely well with a numerical integration of the Schroedinger equation for the exact potential [26]. Our calculations show that, under our experimental conditions, tunnelling or quantum reflection occur with non-negligible probability at energies within a few percent of the reflection threshold. Thus a somewhat improved measurement accuracy might permit the observation of tunnelling and quantum reflection. One can also increase the relative importance of the quantum effects by using lighter atoms and a smaller incident energy. This problem has also been considered in Ref. [27].

3. A diffraction grating for atoms at normal incidence

Having created an atom mirror using an evanescent wave, a simple modification can easily make, at least in principle, a diffraction grating for atoms. If we retro-reflect the light that creates the evanescent wave in Fig. 3, we will have a standing wave, and thus a spatially modulated evanescent wave [28]. This creates a grating quite analogous to a transmission grating using a standing wave [29, 30]. The difference is that our grating operates in reflection. Indeed even this type of grating has been demonstrated by other groups in recent years [31]. The phenomenon of diffraction from this type of grating, however, is sufficiently rich that we have spent considerable effort in elucidating how it works.

3.1. *Theory of diffraction of atoms at normal incidence*

In experiments on diffraction of atoms from a transmission grating it is possible to work in a regime in which a semiclassical approximation is valid [29]. One assumes that the atomic motion can be described by a classical trajectory and that only the atomic phase is altered by the laser induced potential. The diffraction pattern in the far field is computed by taking the Fourier transform of the resulting phase modulation. The very important Raman–Nath approximation consists in assuming that the grating potential does not modify the atomic trajectory inside the grating. This considerably simplifies calculations since it is then not necessary to calculate the actual trajectory of an atom flying through a standing wave potential.

At first sight it does not seem that this type of approach is well suited to a reflection grating, because the atomic mirror must obviously strongly modify the atomic trajectories in order to reflect the atoms. However, if the degree of spatial modulation is weak, i.e. if the evanescent wave contains only a weak standing wave component, it is possible to treat the problem as an unmodulated mirror, for which the atomic trajectory is exactly known, and then to introduce the spatial modulation as phase shift of the atomic wavefunction [32]. It is thus possible, even in the reflection case, to treat atomic diffraction as a thin phase grating effect.

A remarkable result of this treatment is that even with a very weak modulation, i.e. with only a small standing wave component in the evanescent wave, an efficient diffraction into the lower orders is possible. To be more quantitative, consider the potential created by a weakly modulated evanescent wave:

$$U(x, z) = U_0 \, e^{-2\kappa z}[1 + \varepsilon \cos(2k_x x)]$$

where k_x denotes the wave vector of the evanescent wave along the surface and ε is related to the ratios of the amplitudes of the two laser waves creating the grating. The corresponding equipotential surfaces are sinusoidal with a peak-to-peak height of ε/κ. The diffraction into the first two orders will be efficient if this height is comparable to $\lambda_{dB}/2\pi$. Since the atomic de Broglie wavelength is about 100 times smaller than the optical wavelength in our experiment, a value of ε of order 10^{-2} is sufficient to cause significant diffraction.

3.2. *Experimental observation of diffraction*

To create this weak modulation we retroreflect only a very small fraction of the laser intensity which creates the mirror. Since the modulation results from an interference between the two oppositely propagating laser beams, ε represents the ratio of their amplitudes and therefore the ratio of their intensities must only be of order 10^{-4} to efficiently diffract the atoms. To observe diffraction we use a CCD camera placed above the probe beam as shown in Fig. 3 to image the fluorescence of the diffracted atoms. Some of our experimental data showing a spatial profile of this fluorescence for various values of ε are shown in Fig. 6.

Although our resolution does not permit us to resolve adjacent peaks, our data clearly suggest diffraction. We can analyze the data quantitatively by using the profile for $\varepsilon = 0$ as our resolution function and convolving this function with the expected diffraction pattern. The expected [32] intensity of diffraction order n is given by the Bessel function, $J_n^2[2\pi\varepsilon/(\lambda_{dB}\kappa)]$. Since we are able to independently measure ε, λ_{dB} and κ, we should be able to fit the observed profiles with no adjustable parameters apart from the overall intensity of each profile. When we do this the agreement is not satisfactory. However, if we include the effect of the van der Waals potential, which tends to decrease the slope of the potential close to the atoms' turning point and thus increase the accumulated phase shift in the reflection, we find the smooth curves shown in the Fig. 6. We consider the agreement between the experiment and the thin phase grating theory quite satisfactory. The reader is referred to Ref. [33] for more details of the experiment.

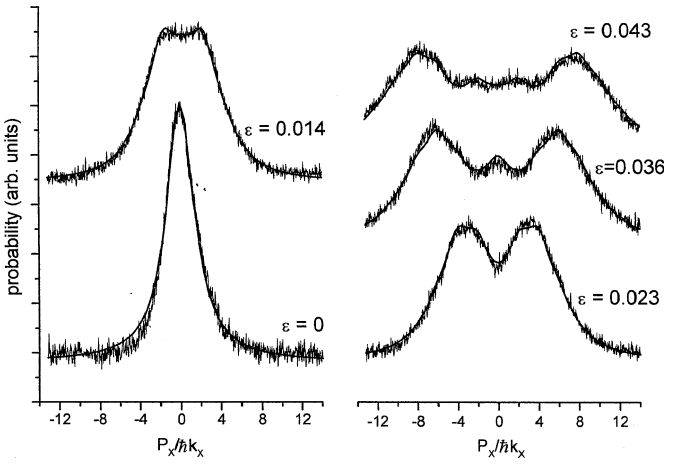

Fig. 6. Spatial atomic profiles observed with the CCD camera in the diffraction experiment. The horizontal coordinate has been converted to an equivalent momentum along the x axis. The parameter ε describes the degree of modulation in the diffraction grating (see Section 3.1).

3.3. *Sensitivity to surface roughness*

The above experiment has allowed us to partially confirm another observation and its interpretation that we have made on evanescent wave mirrors. In Ref. [34] we reported that the reflection of atoms from a mirror is not necessarily specular, but can also be diffuse if the quality of the substrate polish is not sufficiently high. We interpreted this phenomenon as the effect of light scattered by the defects in the surface which can interfere with the evanescent wave producing a corrugated optical potential [35]. The experiment described in the previous section demonstrates the extremely high sensitivity of the atoms to a small amount of light interfering with the evanescent wave. We estimate that from the broadening of profiles such as those in Fig. 6, that we can detect as little as 3×10^{-6} of the incident intensity being reflected back into the evanescent wave. Thus the light scattered by the surface can be thought of as causing a pattern of randomly oriented diffraction gratings on which the atoms "diffract".

4. Conclusions

In these experiments we have shown that there is a great deal of physics in the evanescent wave mirror. We also believe that many interesting experiments remain to be done. We intend to continue to investigate surface roughness with improved transverse momentum resolution. This sort of study should ultimately yield information about the spectrum of surface roughness of the prisms used for the mirror. In some sense one can think of the atoms as an optical near-field probe of the topography of a surface. In addition, we believe that atomic mirrors and diffraction gratings will provide useful tools for further atom optics experiments. In particular, having demonstrated a well controlled diffraction, we hope to use the grating as an atomic beam splitter for interferometry.

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