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An evanescent wave atomic mirror

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A research project at the "Laboratoire d'électronique quantique" consists in a theoretical study of the reflection and diffraction phenomena via an atomic mirror. This paper presents the principle of an evanescent wave atomic mirror. Many groups in the world have constructed this type of atom optics experiments such as in Paris-Orsay-Villetaneuse (France), Stanford-Gaithersburg (USA), Munich-Heidelberg (Germany), etc….. A laser beam goes into a prism with an incidence larger than the critical incidence. It undergoes a total reflection on the plan face of the prism and then exits. The transmitted resulting wave out of the prism is evanescent and repulsive as the pulsation detuning of the laser beam compared to the atomic transition $\Delta = \omega_L - \omega_0$ is positive. The cold atomic sample interacts with this evanescent wave and undergoes one or more elastic bounces by passing into backward points in its trajectory because the atoms' kinetic energy (of the order of the μeV) is less than the maximum of the dipolar potential barrier $\hbar\Omega^2/\Delta$ where Ω is the Rabi pulsation [1]. The dipolar potential with which interact the slow atoms is obtained for a two level atom in a case of a dipolar electric transition (D_2 Rubidium transition at a wavelength of 780 nm delivered by a Titane-Saphir laser between a fundamental state $J_f = 1/2$ and an excited state $J_e = 3/2$). This potential is corrected by an attractive Van der Waals term [2].

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1. Introduction

The reflection of cold atoms on an evanescent wave atomic mirror is based on the interaction of the atom with an inhomogeneous electromagnetic field E(r,t). In the case where the interaction potential is repulsive, the reflection is obtained when the maximum of the potential is larger than the kinetic energy of the atoms at the entrance of the potential. The case of an exponential potential is illustrated in Fig. 1.

Above the prism, the amplitude of the laser field decreases exponentially with the distance to the prism. The laser frequency is adjusted above the atomic transition (blue detuning Δ). When the atom enters the evanescent wave (TE polarised in our case), it undergoes a repulsive dipolar force.

The atom is repelled towards the zones of weak field. It submits a reflection.

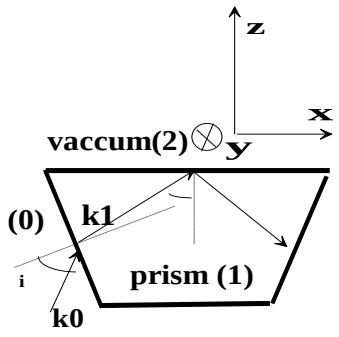

Fig. 1. Laser diagram within the prism. The second interface is from (1) to (2).

The amplitude of the electric field in each region is as follows:

$$\mathbf{E_0} = A.\mathbf{e_y}.\exp\{.(k_0.r - \omega_L t)\} + cc \quad (1)$$

$$\mathbf{E_1} = B.\ \mathbf{e_y}.\exp\{i.(k_1.r - \omega_L t)\} + cc \quad (2)$$

$$\mathbf{E_2} = C.\ \mathbf{e_y}.\exp\{i.(k_2.r - \omega_L t)\} + cc \quad (3)$$

where $\mathbf{e_y}$ is the unity polarisation vector.

$$\text{We have: } \mathbf{k_2} = k_x.\mathbf{e_x} + i.\kappa.\mathbf{e_z} \quad (4)$$

$$|k_0|^2 \sim (\omega_L / c)^2 = \left|k_L^{\,2}\right| \quad (5)$$

$$\text{Thus} \quad \kappa = k_0.\sqrt{n^2.\sin\theta_1^{\,2} - 1} \quad (6)$$

$$k_x = k_0.n.\sin\theta_1 \quad (7)$$

$$\mathbf{E_2} = C.\ \mathbf{e_y}\exp\{-\kappa.z\}.\exp\{i.(k_x.x - \omega_L t)\} + cc \quad (8)$$

The resulting wave is evanescent: it decreases exponentially along Oz and is progressive along Ox. We define the transmission coefficients in amplitude at the prism interfaces as follows:

$$t_{01} = B / A \text{ for the first interface} \quad (9)$$

$$t_{12} = C / B \text{ for the second interface} \quad (10)$$

In the regions (0) and (2), the intensities are given by:

$$I_0 = ½.c.\varepsilon_0. E_0^2 \quad (11)$$

where E_0 is the amplitude of the electric field in region (0) which is vacuum

$$I_2 = ½.c.\varepsilon_0. E_2^2 \quad (12)$$

Inside the prism of refraction index n, the intensity is:

$$I_1 = ½.c.\varepsilon_0. n. E_1^2 \quad (13)$$

We define the following transmission coefficients in intensity (called transmission factors) as:

$$T_{01} = I_1 / I_0 = n.|t_{01}|^2 \quad (14)$$

$$T_{12} = I_2 / I_1 = |t_{12}|^2 / n \quad (15)$$

The expression of the coefficients is more complex when we take into account the TM and TE polarisations of the electric fields [3].

The atomic reflection on the evanescent wave is possible because of the dipolar coupling between the atom and the field. The dipolar potential is simply equal to the light shift $\Lambda(r)$:

$$U_{dip}(r) = \hbar .\Lambda(r) \approx \hbar .\Omega^2(r) / 4\Delta \quad (16)$$

where $\hbar .\Omega(r) = \boldsymbol{\mu}. \mathbf{E_2}(r)$ and μ is the dipolar atomic momentum.

Precisely for an evanescent wave, the dipolar potential is written like:

$$U_{dip}(z) = \hbar .\Lambda(z=0).\exp(-2.\kappa.z) \quad (17)$$

In fact, the atoms are cooled and captured in a magneto-optical trap placed at a distance of the order of the cm above the prism surface.

The dipolar potential is repulsive for a positive detuning ($\Delta > 0$). The atoms are repelled towards the regions of weak field.

A rebound is possible when the atom's energy is less than the maximum of the corrected dipolar potential of the interaction of the atom with the dielectric surface. The rebound at a longitudinal distance z_r of the atomic trajectory occurs when the incident kinetic energy in region (2) is equal to the dipolar energy, i.e,

$$\frac{1}{2} m.v_2^{2\,(inc)} = \hbar . \Lambda(z=0) .\exp(-2.\kappa.z) \quad (18)$$

This is the case at weak saturation, i.e, when $s << 1$ where

$$s = 2.\frac{\Omega^2}{\Gamma^2}\frac{1}{1+4.\frac{\Delta^2}{\Gamma^2}} \quad (19)$$

In the evanescent wave, the atoms are not simply submitted to the dipolar potential. When the atoms approach closely to the prism surface, the interaction potential between the dipole of the atom and its image in the dielectric has to be taken into account. It is the Van der Waals attractive potential. For an atom in a determined energy state (fundamental level), the mean value of the atomic dipole is null and the Van der Waals interaction is due to the fluctuations of the dipole in this level.

We know in the case of the Lennard-Jones approximation (L.J) (distance between the atom and its image of the order of $\lambda_L / 2\pi$ or much smaller than $\lambda_L / 2\pi$) that we can neglect the propagation time of the fields over this distance. For distances where the interaction of the atomic dipole and its image is instantaneous, we refer to a quantum electrodynamic calculation (QED) where the term $\frac{1}{z^3}$ is replaced by the law $\frac{1}{z^4}$ [4]. This is the case for distances z much larger than $\lambda_L / 2\pi$. See Fig. 2 for the plot of the Van der Waals potential (D_2 transition at 780 nm for the Rubidium atom). Reference [5] gives indications on the $1/z^3$ electrostatic calculation of the Van der Waals potential. We give the total potential:

$$U_{tot}(z) = U_{dip}(z) + U_{VdW}(z) \quad (20)$$

$$= \hbar.\Lambda(z=0).\exp(-2.\kappa.z) - \hbar\Gamma\frac{A_{VdW}(z)}{(k_L.z)^3} \quad (21)$$

where Γ is the natural linewidth of the excited state.

$A_{VdW}(z) = A_{LJ}$ or $A_{VdW}(z) = f_{QED}(z).A_{LJ}$ following the taken model where:

$$A_{LJ} = -\frac{n^2 - \left\langle f\left|\mu^2\right|f\right\rangle k_L^3}{n^2 + 48\pi\varepsilon_0\hbar\Gamma} \quad (22)$$

$\langle\mu^2\rangle$ is the mean value of the electrostatic dipole which depends only upon the fundamental state.

We note that in the general case, the potential is not purely exponential as we must take into account the Van der Waals potential describing the interaction between the atom and the prism surface. The evanescent wave mirror is realised by utilising the total reflection of a laser beam within the prism. When the atom enters the evanescent wave, it is submitted to a repulsive dipolar force resulting from the interaction between the atom and the evanescent laser field: the atom undergoes a reflection.

We give the dipolar potential describing the interaction between the atom and the evanescent wave when the polarisation is taken into account (Fig. 3). We will not present the expressions of the light shifts for a $J_f = 1/2 \rightarrow J_e = 3/2$.

The details of the Clebsch-Gordon coefficients for a transition $\left|f, Jf = 1/2, MJf\right\rangle \rightarrow \left|e, Je = 3/2, MJe\right\rangle$

for all the polarisations $\pi, \sigma+$ *and* $\sigma-$ corresponding to the new defined base (**e_π, e_+ , e_-**) won't be given here. See reference [3].

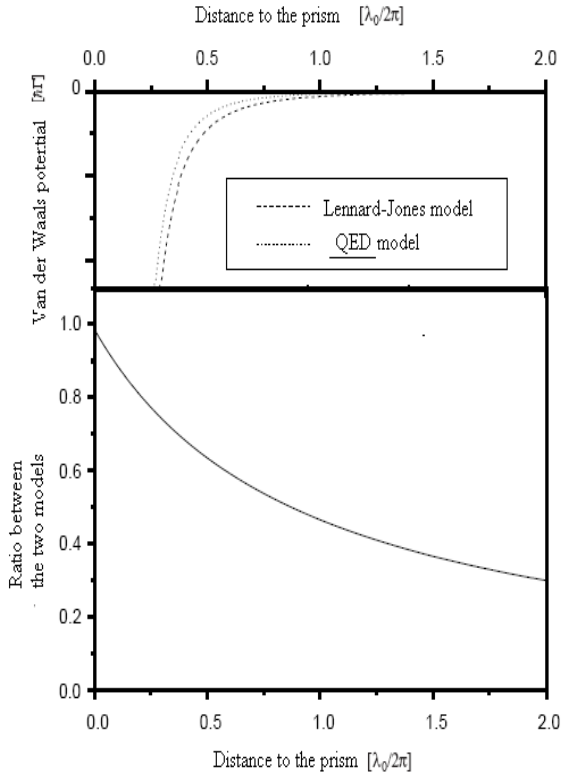

Fig. 2. Van der Waals potentials in both QED and Lennard-Jones Models ($\lambda_0 = \lambda_L$).

For any distance and especially for mean distances z, the Van der Waals potential is written as [6]:

$$U_{VdW}(z) = -\frac{\hbar}{8\pi^2 c^3}\int_0^\infty d\omega.[\,\omega^3.\alpha(\omega).Re\left(\int_0^1 dp + \int_0^\infty dp\right).H(p,\varepsilon).\exp(-2ip\omega z/c)\,] \quad (23)$$

where $H(p,\varepsilon)=\frac{-p+\sqrt{\varepsilon-1+p^2}}{+p+\sqrt{\varepsilon-1+p^2}} + (1-2p^2)\frac{-\varepsilon p+\sqrt{\varepsilon-1+p^2}}{+\varepsilon p+\sqrt{\varepsilon-1+p^2}}$ (24)

p is the atomic momentum, α(ω) is the atomic polarisability and ε is the dielectric constant of the surface.

The atomic polarisability is written as:

$$\alpha(\omega)=\alpha(0).\frac{\omega_0^2}{\omega_0^2-\omega^2} \quad (25)$$

We can use this expression of the Van der Waals interaction for small distances ($z << \lambda_0/2\pi$). A_{QED} = 0.112 for n = 1.869. We find approximately the same value as for the Lennard-Jones calculation: $A_{L,J}$ =0.113.

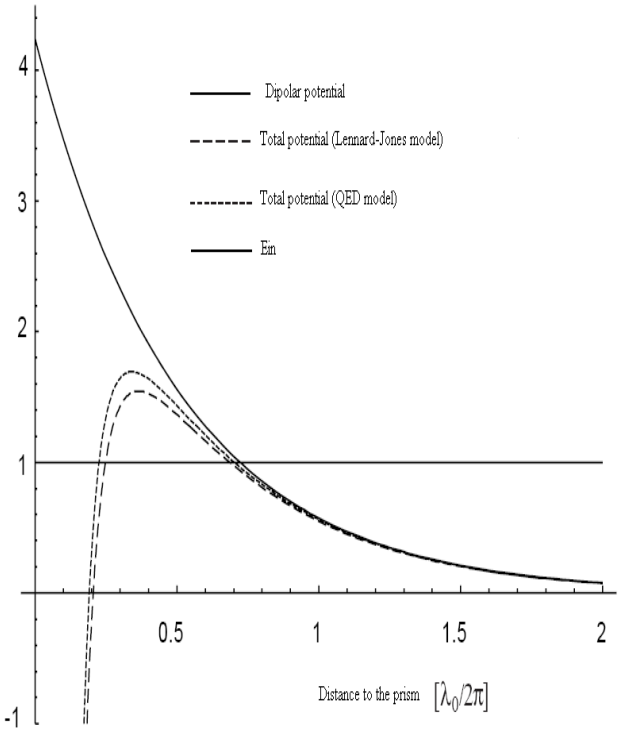

Fig. 3. Total potential in the L. J model and the QED model.

When the undulatory nature of the atoms is not considered, the rugosity is determined by the quadratic fluctuations of the angular distribution of the atomic reflection compared to the direction of the specular reflection.

Fluorescence imaging of the atomic cloud after reflection enabled a quantitative study of the roughness of the mirror.

A Monte Carlo simulation of atoms bouncing on a perfectly flat mirror, including the distribution in position and velocity of the atoms, the eventual presence of a slit, the pulsed nature of the mirror, the detection time and the diffusion of the atoms in the probe beam allow to calculate the resolution function which defines the expansion of the atomic cloud due to the roughness of the mirror.

A high resolution study of the specularity of the atomic reflection from an evanescent wave mirror using velocity selective Raman transitions has been done by A. Aspect and coworkers [7]. We observe a double structure in the velocity distribution after reflection: a peak consistent with specular reflection and a diffuse reflection pedestal whose contribution decreases rapidly with increasing detuning. The diffuse reflection is due to two distinct effects: spontaneous emission in the evanescent wave and roughness in the evanescent wave potential

whose amplitude is smaller than the de Broglie wavelength of the reflected atoms. The atomic reflection is diffuse rather than specular if the surface roughness is comparable to the wavelength of the incident atoms [7]. We introduce the spatial coherence function of the reflected matter waves in a natural manner (Born approximation). The distributions are calculated by taking the Fourier transform of the coherence function.

We'll examine the role of spontaneous emission for which the rate is inversely proportional to the detuning Δ and is responsible of the non specular aspect of the atomic reflection (atomic diffusion). In the contrary, we note that the specularity of the reflection preserves the coherence of the atomic wave packet. The atoms will constitute a probe of the rugosity of the prism surface which can be imperfect or super-polished.

The atomic scattering is sensitive to height variations of the dielectric surface at the scale of the incident atomic wavelength λ_{dB}. The momentum distribution of the scattered atoms, averaged over a large number of samples of the rough surface, gives access to the power spectrum of the surface roughness in this spectral range.

We won't present the details of the calculation performed by the group of A. Aspect but we emphasize that the diffuse atomic reflection from the evanescent wave above a corrugated dielectric surface may serve as a probe of the surface quality at the scale of the atomic wavelength. We note that this surface probe is complementary to optical near-field microscopy.

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