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Quantum wires and quantum dots for neutral atoms

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Abstract. By placing changeable nanofabricated structures (wires, dots, *etc.*) on an atom mirror one can design guiding and trapping potentials for atoms. These potentials are similar to the electrostatic potentials which trap and guide electrons in semiconductor quantum devices like quantum wires and quantum dots. This technique will allow the fabrication of nanoscale atom optical devices.

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1 Introduction

Cooling and trapping techniques developed in recent years allow for the preparation of very cold and dense samples of neutral atoms (for a recent review see [1]). These atoms are so slow that their typical de Broglie wavelength, λ_{dB}, can be on the order of 100 nm or larger which is in the range of the size of mesoscopic structures built using modern nanofabrication technology. Choosing suitable interactions between the neutral atoms and the nanofabricated structure, it should be possible to build mesoscopic quantum devices with atoms guided and/or trapped in designed potentials.

In this paper we will first discuss the basic principles of surface mounted mesoscopic atom optical devices and then describe how to design *quantum wires* and *quantum dots* for neutral atoms. This will be followed by a short discussion of how to load atoms in these mesoscopic guides and traps. Finally we will point to some of the possible applications of such devices.

2 Surface mounted atom optics

Several different interactions between a neutral atom and nanofabricated structures such as a thin wire or a sharp tip (dot) can lead to trapping and guiding. The principal idea is the following: an attractive interaction binds the atom to the wire (dot) and a repulsive interaction, close to the wire (dot) surface, prevents the atom from interacting with the surface. This repulsive interaction is very important because atoms hitting the surface will either be absorbed or scattered inelastically. In most cases this surface will be many orders of magnitude hotter (typically 300 K) compared to the kinetic energy of the cold atoms ($E_{kin} < \mu$eV corresponding to $T <$ mK temperatures). Therefore the atoms are, for all practical purposes, lost if they come in contact with the surface.

In this paper we explore atom optic [2] devices which can be built when combining the strong, short range, repulsive interaction of an atom mirror (evanescent wave mirrors [3–8] or magnetic mirrors [9–11]) and the attractive interaction of a neutral atom in the electric field of a charged wire (dot). By placing charged nanostructures on (or below) an atom mirror, one can design guiding and trapping potentials which are similar to the electric potentials used to trap and guide electrons in semiconductor quantum devices [13] like quantum wires and quantum dots.

The reflection of atoms at an atom mirror is based on a short range (exponentially decaying) repulsive potential (decay length $1/\kappa$):

$$U_m(x) = U_0 \exp(-\kappa x) \tag{1}$$

where x is the distance from the mirror surface. U_m can be created either by a blue-detuned evanescent wave created by total internal reflection (evanescent wave mirror [3–8]) or the magnetic fields of an alternating magnetic pattern (magnetic mirror [9–11]).

The strong position dependent *attractive* potential required to build guides and traps can be created by the strong (inhomogeneous) electric field $\mathbf{E}$. The potential energy for a neutral atom with electric polarizability α (for simplicity we will assume α to be a scalar) in the electric field is then given by

$$U_{pol} = -2\pi\epsilon_0\alpha|E(r)|^2. \tag{2}$$

For the ground state of a neutral atom U_{pol} is always attractive.

Since the repulsive potential is short range, on the order of the wavelength of light for the evanescent wave mirror, the attractive Van der Waals interaction between the atom and the surface is important [12] and has to be taken

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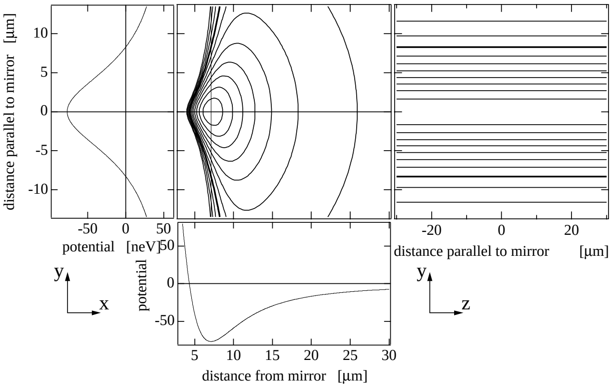

Fig. 1. Typical potential for neutral atom quantum wire. The attractive potential ($1/\rho^2$) is created by the interaction of the induced dipole moment in the electric field of the charged wire mounted directly on the surface of an atomic mirror. The action of the atomic mirror (evanescent wave or magnetic mirror) prevents the atom from reaching the surface and creates a quantum channel close to the surface. The central contour graph shows the potential defining the quantum channel. The two adjacent plots give the potential in a direction orthogonal to the charged wire and orthogonal/parallel to the mirror surface. Distances are given from the location of the charged wire and the surface of the atom mirror.

into account in the calculations. It leads to a modification of the trapping potential, drawing the minimum closer to the surface of the atom mirror.

3 Neutral atom quantum wires

A simple, mesoscopic one dimensional trapping potential for neutral atoms can be built by mounting a charged wire on an atomic mirror.

The interaction between a neutral atom and the electric field of a thin wire with line charge q along the z-direction is given by (in cylindrical coordinates: $\rho = \sqrt{x^2 + y^2},\ \phi,\ z$):

$$U_{pol}(\rho) = -\frac{1}{2\pi\epsilon_0}\frac{\alpha\, q^2}{2\rho^2}\,. \tag{3}$$

The potential $U_{pol}(\rho)$ is always attractive and diverges like ρ^{-2} as $\rho \to 0$. The motion can not be stabilized by angular momentum and the interaction potential (Eq. (3)) does not lead to stable orbits [14]. Atoms either get absorbed on the wire surface or they escape towards infinity. Mounting such a charged wire at the surface of the atom mirror allows the combination of the attractive $1/\rho^2$ potential (Eq. (3)) with the repulsive potential of the atom mirror $U_m(x)$ (Eq. (1)).

$$U_{guid}(\mathbf{x}) = U_m(\mathbf{x}) + U_{pol}(\rho). \tag{4}$$

This creates a potential tube for the atoms as shown in Figure 1 which can be viewed as a waveguide for neutral atoms, the atom optical analog to a gradient index optical fiber, the interaction potential being equivalent to a refractive index.

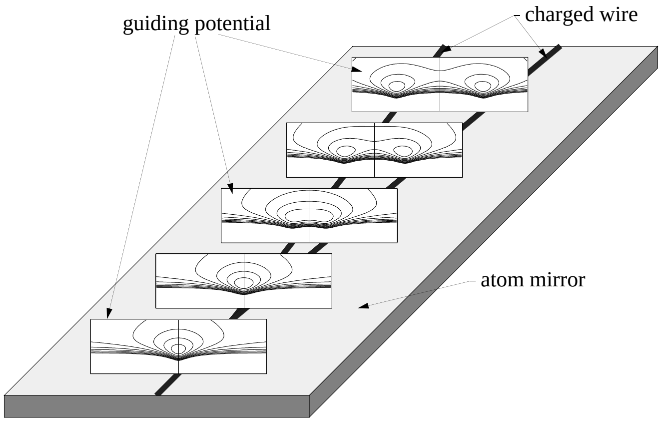

Fig. 2. Schematics of a quantum wire beam splitter. The charged wire mounted on an atomic mirror is split in Y shape. The resulting guiding potential is shown in selected planes along the quantum wire beam splitter.

Far above the atom mirror the guiding potential $U_{guid}(\mathbf{x})$ (Eq. (4)) is dominated by $U_{pol}(\rho)$ which behaves like $1/\rho^2$. Accordingly there is an infinite number of bound states and the eigenenergies for the high-lying states follow an exponential law. However one can adjust the parameters so that there are only one or a few deeply bound states. In this regime a matter wave fiber with quasi single-mode propagation properties can be built.

Mounting the charged wire on an atomic mirror to create such a waveguide allows one to use the well-developed nanofabrication techniques to lithographically write the wires, in any geometrical structure, *i.e.* straight, bent or in form of a Y *etc.* One could create beam splitters (see Fig. 2), interferometers or even complex networks for guided neutral atoms. Furthermore additional electrodes located close to the wire can be used to modify the guiding potential at demand. One can easily imagine designing switches, gates, modulators *etc.* for guided atoms.

The above mentioned techniques of manipulating the guiding (trapping) potentials for neutral atoms is similar to techniques used in quantum electronics to create quantum wells and quantum wires [13], therefore the name *neutral atom quantum wires*.

Typical parameters for such neutral atom guides are given in Table 1. The quantum wires based on the evanescent wave mirror have much tighter confinement and are closer to the mirror surface. This is mainly due to the much shorter decay length of the evanescent wave potential ($\sim 0.1\,\mu$m) as compared to the magnetic interaction ($\sim 1.5\,\mu$m) in reference [11]. Secondly the spontaneous scattering rate in the evanescent wave based quantum wires is quite high (typically a few kHz for a simple mirror using internal reflection). This rate can be reduced by increasing the detuning of the evanescent wave, but then higher laser power is needed for the same mirror potential height. This may be achieved by confining the mirror,

Table 1. Typical parameters for Li and Rb atoms guided in neutral atom quantum wires located above a typical evanescent wave mirror and a typical magnetic mirror. Ground state properties are calculated using a harmonic oscillator approximation of the trapping potential near the minimum. The z-direction is perpendicular to the mirror surface x-direction is parallel to the mirror surface and orthogonal to the wire.

atom	wire	potential		ground state properties				
	charge [pC]	depth [neV]	distance [μm]	frequency [kHz] z	x	size [μm] z	x	scat. rate [kHz]
evanescent wave mirror: U_m=1 μeV $\kappa = 0.1$ μm $\Delta = 1000\Gamma$								
Li	0.33	-5.05	0.60	211	125	0.083	0.107	4.6
Rb	0.22	-4.47	0.610	57	33	0.046	0.060	5.2
magnetic mirror: $U_m = 6.4$ μeV ($B_0 = 1100$ G) $\kappa = 1.5$ μm (9.5 μm magnetization)								
Li	1.05	-0.063	20	1.15	0.37	1.12	1.98	-
Li	15.7	-75.5	7.2	56	43	0.161	0.183	-
Rb	0.43	-0.017	22	0.166	0.05	0.85	1.55	-
Rb	10.8	-64.9	7.5	14.8	10.8	0.090	0.105	-

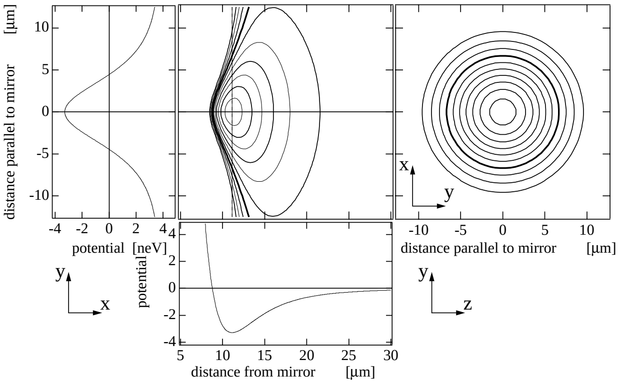

Fig. 3. Typical potential for neutral atom quantum dot. The attractive potential ($1/r^{-4}$) is created by the interaction of the induced dipole moment in the electric field of a point charge mounted directly on the surface of the atomic mirror. The action of the atomic mirror prevents the atom from reaching the surface and creates a microscopic trap. The central contour graph shows the potential defining the quantum channel. The two adjacent plots give the potential in a direction orthogonal to the charged wire and orthogonal/parallel to the mirror surface. Distances are given from the location of the point charge and the surface of the atom mirror.

and therefore the light, to only a small region around the wire by guiding the laser light in a planar, transversely-confined waveguide which may even enhance the evanescent wave. With such special nanofabricated light guides producing the repulsive evanescent wave a reduction of the scattering rate by 2-4 orders of magnitude should be feasible.

The guides formed by the magnetic mirrors are much further above the surface and can be made much deeper due to the stronger repulsive mirror potential. In general the magnetic mirror based quantum wires seem to be more promising for coherent waveguides, especially since choosing special magnetic materials with higher magnetization and with smaller magnetic structures [20] for the magnetic mirror will allow for deeper and more confined quantum wires. One can also estimate the lifetime of atoms in these quantum wires due to tunneling to the mirror surface, and found it to be much longer than 1000 s in any of the discussed cases.

Using highly charged wires the lower-lying eigenstates in the neutral atom quantum wire can be localized in transverse direction to much smaller than the wavelength of light used to manipulate the atoms (*i.e.* 670 nm for Li atoms). Atoms will be trapped in the Lamb-Dicke regime. With better atomic mirrors it is even conceivable to separate the bound states by more than the linewidth of the optical transition allowing sideband cooling of neutral atoms similar to ions in ion traps [21].

4 Neutral atom quantum dots

In analogy to the above discussed quantum wires, microscopic traps (the analog to quantum dots) can be created by mounting a charged tips (point) at or close beneath the atom mirror surface.

As an example we will discuss here the simplest case of a point charge on the surface of an atom mirror. The point charge creates an attractive $1/r^4$ interaction potential:

$$V_{pol}(r) = -\frac{1}{8\pi\epsilon_0}\alpha\frac{1}{r^4} \tag{5}$$

together with the atomic mirror it will create a potential well

$$V_{trap}(\mathbf{x}) = U_m(\mathbf{x}) + V_{pol}(r) \tag{6}$$

that forms a microscopic cell for the atoms, such as that shown in Figure 3. It can be viewed as the atom optical analog to a quantum dot.

Far above the atom mirror the trapping potential $V_{trap}(\mathbf{x})$ (Eq. (6)) is dominated by $V_{pol}(r)$ (Eq. (5))

Table 2. Typical parameters for Li and Rb atoms trapped in neutral atom quantum dots above a typical evanescent wave mirror and a typical magnetic mirror. Ground state properties are calculated using a harmonic oscillator approximation of the trapping potential near the minimum. The z-direction is perpendicular to the mirror surface x-direction is parallel to the mirror surface and orthogonal to the wire.

atom	point	potential		ground state properties				
	charge	depth	distance	frequency [kHz]		size [μm]		scat. rate
	electrons	[neV]	[μm]	z	x	z	x	[kHz]
evanescent wave mirror: $U_m = 1$ μeV $\kappa = 0.1$ μm $\Delta = 1000\Gamma$								
Li	141	-0.59	0.72	88	60	0.13	0.16	1.5
Rb	112	-0.99	0.65	32	27	0.061	0.067	2.6
magnetic mirror: $U_m = 6.4$ μeV ($B_0 = 1100$ G) $\kappa = 1.5$ μm (9.5 μm magnetization)								
Li	10000	-0.005	23	0.42	0.13	1.86	3.3	-
Li	80000	-3.2	11	14	9	0.33	0.41	-
Rb	10000	-0.012	21	0.19	0.07	0.78	1.34	-
Rb	63000	-5.0	10	4.9	3.8	0.16	0.18	-

and behaves like $1/r^4$, consequently there will be a *finite* number of bound states. For a specific set of parameters (weak potentials) there will be *one* single bound state.

Typical parameters for such neutral atom quantum dots are given in Table 2. The potentials are not as deep as for the quantum wires, but in general the discussion about the quantum wire potentials given above also hold here. Again using highly charged dots the lower-lying eigenstates in the neutral atom quantum dots can be localized to better than the wavelength of light and the atoms will be trapped in the Lamb-Dicke regime. With stronger atom mirrors it is even conceivable to separate the bound states by more than the linewidth of the optical transition allowing sideband cooling similar to ions in ion traps [21].

5 Loading atoms in mesoscopic surface traps

An important question now arises, how to load atoms in these microscopic traps or guides. Atoms have first to be trapped and cooled without coming in contact with the mirror surface. The evanescent wave mirror can repel all ground state atoms, and atom traps close to or even at an evanescent wave mirrors were recently demonstrated [22,23]. Therefore loading atoms into mesoscopic traps will be easier in the case of the evanescent wave mirror based devices. This is harder for the magnetic mirror, since scattering light from atoms changes their internal magnetic states, and the atoms in wrong magnetic substrates will not be reflected, but attracted to the mirror surface. So loading schemes like the one proposed by Hinds *et al.* [24] will have to be used to transfer atoms from a MOT to a surface trap.

One loading scheme can be based on a modification of the magneto optic surface trap (MOST) as demonstrated by Mlynek's group in Konstanz [22]. A sizable number of atoms loaded and cooled in a standard MOT at some distance to the surface and then shifted fast (in a few ms) where they are then held in the region of the mesoscopic traps or guides by the magneto optic surface trap. By such a procedure, loading far from the surface and then shifting the atoms to te surface, one can transfer the density of a regular MOT on to the surface. By simultaneously switching off the MOST and switching on the charged structures one can trap some atoms in the mesoscopic traps or guides. The loading probability can then be estimated by the product of trap (guide) volume times atom density. Using a standard MOT density of 10^{11} cm^{-3} and a guide cross section of 1 μm^2 one can expect 100 trapped atoms for 1 mm guide length. One can think of enhancing the loading probability by switching the electric trapping field on during the MOST. This will provide an additional potential minimum to attract the cold atoms, similarly to loading atoms in a FORT [25].

A second promising loading scheme can be based on the gravito optic surface trap [23]. There atoms are loaded and cooled in a small (μm size) layer close to the surface of an evanescent wave mirror. This is exactly the region where the atoms will then be trapped in the mesoscopic traps. Switching on the trapping electric fields during the final stage of the loading should again enhance the probability to load the atoms in the small mesoscopic traps.

One can also think of a two step process: first loading atoms in one of our recently demonstrated atom guides created by a current carrying wire [26]. These guides can transport the atoms to the surface mounted atom optical devices. Such a schema has the advantage that it seems straight forward to load a BEC into the wire guide which would then transport the atoms and connect them mode-matched to the quantum wires.

6 Outlook

We have shown that by mounting changeable nanofabricated structures on the surface of an atom mirror, one can design and create very versatile microscopic and mesoscopic potential structures for neutral atoms. These neutral atom quantum wires and quantum dots have many advantages compared to the other guides [15].

- a) The potential can be designed at will, using well-known technology. It is easy to achieve very small guides, and single mode propagation or storage in the ground state should be possible. In addition these guiding and trapping potentials can be easily modified by applying fields to additional electrodes. Loading of the guides and traps seems feasible using known cooling and trapping technology.
- b) In contrast to the guiding and trapping in a hollow optical fiber [19] the neutral atom quantum wires and dots are in the open, above a surface, and the desired UHV environment, which is essential for coherent trapping or guiding can be easily realized.
- c) Using use the well-developed nanofabrication techniques the principles of guiding can be easily extended to more complicated structures like a beamsplitter, an interferometer, or even integrated atom optical devices, like interferometers and inertial sensors or complex quantum networks for guided neutral atoms. Furthermore additional electrodes located close to the wire can be used to modified the guiding potential on demand. One can easily imagine designing switches, gates, modulators *etc.* for guided atoms.
- d) Having the atoms trapped in microscopic traps near a surface will allow the integration of atom optics and light optics. Waveguides for light can be nanofabricated on the atom mirror surface. They can be used to address individual neutral atoms in quantum dots, and additional electrodes can be used to shift the atoms in and out of resonance. This will allow the construction of integrated optics devices for atom light manipulation which might be used to build quantum registers for quantum communication and quantum computation [27].
- e) Atom optics is inherently non linear allowing easy coupling between atoms in different channels of a waveguide network, just by using waveguide beam splitters. If one can control the motion of the atoms in these guides to such an extent that one can send independent atoms simultaneously onto a beam splitter, then one will be able to entangle independent atoms by their mutual interaction. This might allow to construct quantum computation gates and networks using atoms propagating in these waveguides [27].

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