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Quantum reflection engineering: The bichromatic evanescent-wave mirror

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We explore the design of atom-optic components, such as mirrors, to manipulate ultracold atoms. We show that it is possible to enhance significantly quantum effects by engineering sharp features in the interaction potential between atoms and the component. We illustrate the concept by calculating the reflection probability for ultracold sodium atoms incident on a bichromatic evanescent-wave atomic mirror created by lasers red and blue detuned from resonance with intensities and detunings chosen to enhance quantum reflection of a purely attractive potential. With realistic parameters for sodium atoms incident on glass at 10 cm/s, up to 30% reflection can be obtained.

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The realization of atomic condensates provides coherent matter wave for atom-optics experiments [1]. Atom-optic components can be designed and used to guide, manipulate, and trap atoms [2], as well as to study fundamental aspects of quantum mechanics, such as quantum suppression [3] or above barrier quantum reflection and tunneling. In this paper, we show that by desiging sharp variations in the atom-component interaction potential, enhanced quantum effects can be achieved. We illustrate this general feature using a realistic setup: above barrier reflection with evanescent-wave mirrors.

Atoms incident on a dielectric-vacuum interface can stick to the surface or be reflected. Quantum mechanics tells us, perhaps counter intuitively, that as the velocity of the incoming atoms decreases, the reflection probability approaches 1, due to quantum reflection from the purely attractive van der Waals (vdW) potential. Such quantum reflection of hydrogen from liquid ^{4}He was observed [4,5]. The incident velocities of atoms should be extremely small to see any quantum reflection from other bare atom-surface vdW potentials [6]. Shimizu *et al.* used the fact that only the component of the velocity perpendicular to the surface needs to be extremely small and observed quantum reflection of neon atoms [7]. They also showed that quantum reflection can be selectively enhanced by rapidly changing structures on the reflecting surface. Recently, quantum reflection far from the threshold limit has also been observed [8].

Reflection from evanescent-wave atomic mirrors has been studied: such mirrors are obtained when detuned light undergoes total internal reflection inside a dielectric prism [9–22]. Without lasers, the atom-surface potential is purely attractive [23–26]. Reflection from blue-detuned (repulsive) mirrors was used to measure the vdW force [22]. The influence of vdW potentials on diffraction of atoms through transmission gratings was likewise measured [27]. Two colors evanescent-wave potentials [17] together with hollow laser beams were proposed [20] to create atom trap where evaporative cooling can take place [21]. To illustrate how enhanced quantum effects can be engineered by designing sharp features in atom-component potentials, we investigate a realistic system based on a bichromatic evanescent-wave setting (Fig. 1). Here, we study scattering from this potential, complementing previous theoretical studies of reflection from purely red-detuned evanescent mirrors [18], and Bragg reflection from a periodic optical potential [19]. We show below that while the combination of the vdW potential and a red-detuned evanescent-wave does not enhance quantum reflection as compared to the pure vdW potential, the bichromatic scheme allows for a significant increase in above barrier reflection.

Atoms incident on evanescent-wave mirrors move in an effective potential produced by the combination of a light-induced potential and the attractive atom-wall interaction. Neglecting spontaneous emission and internal transitions, the optical dipole potential for the atom is proportional to the intensity of the laser beam which drops exponentially with the distance outside the surface of the dielectric prism, and inversely proportional to the detuning from the resonance frequency. When the laser is blue detuned the optical potential is repulsive and a potential barrier is formed. If instead a red-detuned evanescent wave is used, the effective potential becomes attractive everywhere. Any reflection from such a "red mirror" would be a purely quantum effect. However, even for small velocities of the incoming atoms, the reflection probability from a red mirror would be extremely small ($\sim 10^{-5}$ for sodium atoms at 10 cm/s). To design a component enhancing quantum effects, we suggest a bichromatic mirror created by two evanescent laser fields, one red detuned and one blue detuned from the atomic resonance. The effective potential can be made attractive everywhere by choosing a weak enough blue-detuned field: any reflection would then be a pure quantum effect.

In the limit of incoming atoms at zero velocity, Wigner threshold laws come into play and the reflection probability approaches 1 [28]. Our interest here is connected to this limit, yet we ask a different question: given some small but finite velocity of the incoming atoms, achievable with today's technology [29], can we construct an evanescent-wave mirror with a purely attractive potential but with high reflectivity? In addition, we require that the reflection occurs far enough from the prism itself, so that we could treat the system without taking into account surface phenomena.

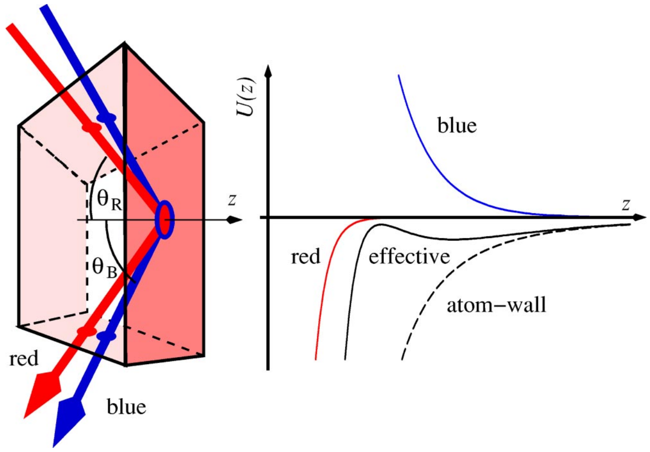

FIG. 1. Bichromatic evanescent-wave mirror. In the left panel, we show a schematic of the prism and the two lasers, defining θ_R and θ_B. The right panel illustrates the various components contributing to the effective potential.

In the bichromatic mirror considered here (Fig. 1), two exponentially decaying optical potentials [red (R) and blue (B) detuned] and the attractive atom-wall interaction add up to generate the effective potential,

$$U(z)=C_B e^{-2\kappa_B z}-C_R e^{-2\kappa_R z}-\frac{C_3}{z^3}, \tag{1}$$

with $\kappa_{B/R}=k_{B/R}\sqrt{n^2\sin^2\theta_{B/R}-1}$, where z is the distance from the prism surface, n is the index of refraction of the dielectric, $\theta_{B/R}$ are the incident angles of the laser beams, and $k_{B/R}$ are their wave numbers. The maximum of the optical potentials at $z=0$, $C_{B/R}$, is determined by the intensity $I_{B/R}$ and the detuning from the resonance $\delta_{B/R}$. For large detuning, we have [30] $C_{B/R}\simeq I_{B/R}d^2/8\hbar\epsilon_0\delta_{B/R}$, where d is the atomic dipole moment and ϵ_0 is the vacuum permittivity. If the lasers are tightly focused, the intensity profiles may need to be taken into account [30]. In the case of above barrier reflection from blue-detuned evanescent mirror, the tight focusing may obscure the experimental ability to distinguish between classical and quantum reflection. We have suggested ways to overcome this difficulty [30]. In a purely attractive potential, however, every reflection is a quantum reflection, and the tight focusing is less of a concern to the interpretation of the results. We use here the simplest approximation for the atom-wall interaction—the Lennard-Jones potential [23]. Extending our treatment to more accurate potentials, including, in particular, retardation effects, is straightforward. We have previously considered retardation effects on reflection from the purely vdW potential and from a blue-detuned mirror [30]. It was shown that for the cases studied quantum reflection from the retarded potential is larger than from the non-retarded one. On quantum reflection from pure Casimir-vdW atom-wall potentials see also Ref. [31]. Retardation effects become relevant for z larger than $\lambda/2\pi$, where λ is the atomic transition wavelength, and we leave their study on reflection from the bichromatic mirror to future work. In the Lennard-Jones potential, C_3 is related to the constant $C_3^{\rm metal}$ of a pure metallic wall by $C_3=C_3^{\rm metal}(n^2-1)/(n^2+1)$. The numerical values for Na atoms used in this paper are $n=1.5$, $k_{B/R}=k_L=5.645\times10^{-4}$ a.u., $C_3^{\rm metal}=1.889$ a.u., and $m=41\,907.782$ a.u.

We want to optimize the potential in Eq. (1) for pure quantum reflection, i.e., for a potential everywhere attractive. For given parameters of the two laser beams, the reflection probability R is obtained by assuming perfect sticking at the wall and numerically solving the Schrödinger equation as described in Côté *et al.* [30]. We are free to choose the wave numbers $k_{B/R}$ (and hence the detunings $\delta_{B/R}$), the incident angles $\theta_{B/R}$, and the intensity of each laser at the dielectric-vacuum interface $I_{B/R}$. In this way, we can control $C_{B/R}$ and $\kappa_{B/R}$. But how do we choose the best parameters $C_{B/R}$ and $\kappa_{B/R}$?

A simple way to choose the optimal laser parameters for quantum reflection, which also explains why a similar effect cannot be achieved in a monochromatic mirror, is based on the concept of "badlands" [30]. For quantum reflection to occur, the Wentzel-Kramers-Brillouin (WKB) approximation must be violated. The notion of the badlands is a concept introduced to quantify the extent to which WKB is broken for a given energy of the incoming atoms at each coordinate z. The essential condition for applicability of the WKB approximation is that the de Broglie wavelength $\lambda_{dB}=2\pi\hbar/p$, with $p(E,z)=\sqrt{2m[E-U(z)]}$, varies sufficiently slowly,

$$\Delta(z)\equiv\frac{1}{2\pi}\left|\frac{d\lambda_{dB}}{dz}\right|=\hbar\left|\frac{m}{p^3}\frac{dU}{dz}\right|\ll1. \tag{2}$$

The "badlands" are the regions where the condition (2) is not fulfilled and the "badness" is Δ. Alternative definitions for the badlands are also useful [31]. Note that the badlands are determined by both the potential and the energy. The stronger and wider are the badlands, the higher is the quantum reflection. With Eq. (1), we get

$$\Delta=\frac{\hbar}{\sqrt{2m}}\,\frac{-\kappa_B C_B e^{-2\kappa_B z}+\kappa_R C_R e^{-2\kappa_R z}+\frac{3}{2}C_3/z^4}{[E-C_B e^{-2\kappa_B z}+C_R e^{-2\kappa_R z}+C_3/z^3]^{3/2}}. \tag{3}$$

For Δ to be significant, one needs a small $p(E,z)$ and/or large dU/dz. In addition, we require $U<0$ for all z. The values of the parameters are restricted by experimental constraints [32]. The incident angle must be larger than the critical angle θ_c for total reflection (41.8° here) and roughly smaller than 55° [32]. The wave numbers should be detuned 1 GHz or more from resonance to avoid spontaneous emission. The intensities are typically of the order of 100 mW/mm^2. The values of C_B and C_R will be of the order of 10^{-9} a.u. (or about 6 MHz), while κ_B and κ_R will vary more widely depending on the angles and the index of refraction n. As an example, we consider sodium atoms with $v=10$ cm/s incoming towards a prism with $n=1.5$, and we keep the red-detuned laser beam intensity and detuning at fixed values ($I=100$ mW/mm^2 and $\delta=2\pi\times1.1$ GHz), so that $C_R=1.3\times10^{-9}$ a.u. (or 8.6 MHz): the values of C_B op-

TABLE I. Reflection coefficient R for various parameters. Here, the angle for the blue laser is fixed to 55° (or $\kappa_B = 4.0304 \times 10^{-4}$ a.u.), while the detuning and intensity of the red laser are set to give $C_R = 1.3 \times 10^{-9}$ a.u.

θ_R	κ_R (10^{-5} a.u.)	$C_B = C_B^*$ (10^{-9} a.u.)	R ($v = 10$ cm/s)
42 °	4.8578	4.143	0.284
43 °	12.176	3.641	0.226
44 °	16.529	3.345	0.180
45 °	19.958	3.112	0.142
no laser			0.000011

timizing the reflection coefficient R, labeled C_B^*, will depend on the angles of the beams. We fix θ_B at 55° (with $\kappa_B = 4.0304 \times 10^{-4}$ a.u.), and vary θ_R starting just above $\theta_c = 41.8°$, from 42° to 45°. The parameters are listed in Table I, together with the corresponding reflection coefficients R. As θ_R gets closer to θ_c, R becomes larger: for $\theta_R = 42°$, nearly 30% of the incoming atoms will be reflected by the purely attractive interaction, a large improvement over the 0.001% value without lasers on. The effective potential and badlands are shown in Fig. 2 for the case $\theta_R = 43°$ in Table I: the effect of the combined evanescent waves is drastic, creating a "sharp" structure in the effective potential, and driving the badlands in the regime where quantum effects are significant, hence a large reflection coefficient R. With the red-detuned laser alone, R would be similar to that from the pure vdW potential. Without the red-detuned laser, keeping $U(z) < 0$ would require decreasing the intensity of the blue-detuned laser which, again, would substantially reduce R. Because quantum reflection occurs mainly near Δ maximum [31], Fig. 2 confirms our use of $-C_3/z^3$: here $\lambda/2\pi = 1772$ a.u. (Na), while Δ maximum is located near 1000 a.u.

In Fig. 3, we show R as a function of C_B, while the other

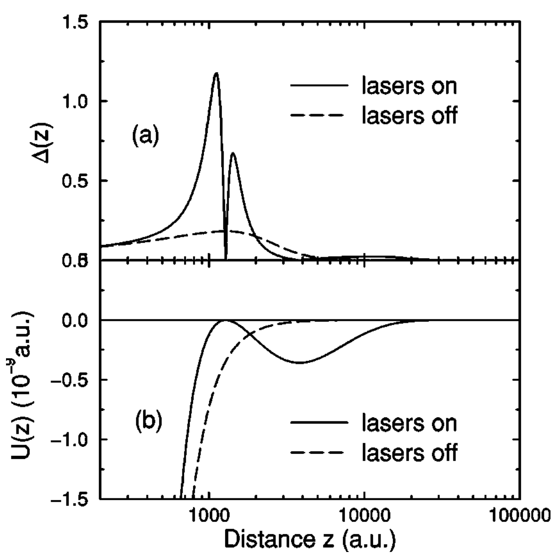

FIG. 2. Comparison of the badlands (a) and the potentials (b) when the lasers are on and off (for $\theta_R = 43°$ in Table I).

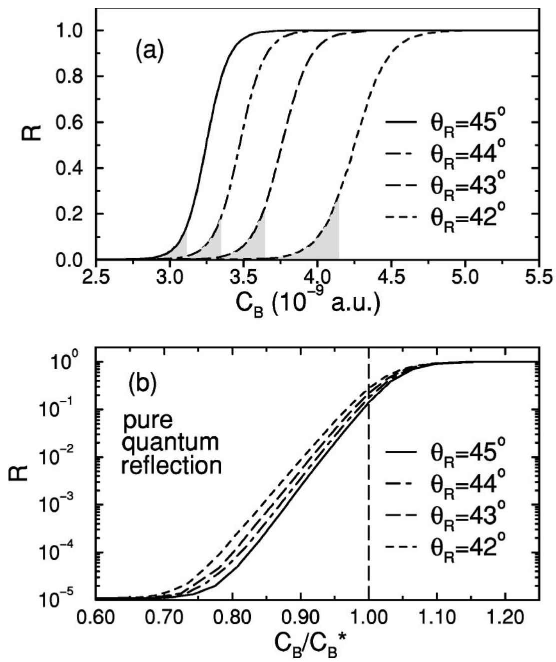

FIG. 3. Reflection coefficient as a function of C_B for various angle θ_R. Here, $C_R = 1.3 \times 10^{-9}$ a.u. and $\theta_B = 55°$. In (a), the shaded regions illustrate parameters for which the effective potential is purely attractive, corresponding to pure quantum reflection. In (b), the same R are plotted in terms of the scaled parameter C_B/C_B^* on a logarithmic scale: $C_B/C_B^* < 1$ corresponds to pure quantum reflection.

parameters have the values listed above. For each angle θ_R, we obtained an S shape for the reflection coefficient R [30], shifted to lower values of C_B as θ_R increases [see Fig. 3(a)], since the blue-detuned laser intensity necessary to produce the feature in the effective potential is smaller for large angles θ_R (see Eq. (1) and Fig. 1). The shaded areas illustrate the region for which the effective potential is purely attractive, hence the corresponding reflection is purely quantal in origin. We note that these shaded regions are more extended for smaller θ_R, translating the fact that R for purely quantum reflection is larger and grows more rapidly with C_B for smaller angles θ_R. To better compare the different curves, we plot them as a function of the rescaled parameter C_B/C_B^* [see Fig. 3(b)]. The logarithmic scale emphasizes the more rapid growth of R for smaller angles, as C_B/C_B^* is increased, in the pure quantum reflection regime. Naturally, the parameter space is much larger than what we show here, and if the experimental constraints can be relaxed, even more dramatic results can be obtained.

In conclusion, we have shown that one can design atom-optic components that optimize quantum effects, in particular, above barrier reflection, by creating features in the interaction potential such that the badlands become significant. We use the bichromatic evanescent-wave mirror as an example. In the future, detailed studies of tunneling and resonances could be performed with this system, and because the exact shape of the potential depends on the long-range atom-wall interaction, sensitivity to retardation could be studied. It remains to be seen whether the purely quantal nature of the reflection would be of interest for practical applications in atom-optical devices. Clearly, coherent reflection can be achieved more easily with a blue-detuned mirror, yet the sensitivity of quantum reflection to the full potential (and especially to sharp variations) may prove useful, as was demonstrated in Ref. [7]. The evanescent-wave setting complements recent nanofabrication approaches to quantum reflection, allowing for high reflectivity for higher incident velocities as well as for modification and control in real time by changing the detuning and intensities of the lasers. Finally, one could employ many lasers to design complicated effective potentials tailored to do specific tasks: the possible applications are practically unlimited.

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