Atom localization using Rydberg-EIT/ CPT with spatially dependent fields

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Rydberg atoms

1. Large size:ranging as n^2 (~1 μm for *n*~100)
2. Small binding energy: $E=(e^2/a_0)*((m-m_e)/m)/*(2(n-\delta_l))$
3. Long radiative lifetime: $n^3(l+1/2)^2 10^{-10}$ (~1 μs)
4. Big dipole matrix elements: $\sim n^2 q_e a_0$
5. Dipole matrix elements sensitive to electric fields: $-\vec{\mu}.\vec{F}$
6. Interact via dipole-dipole interaction: Vdd $=\dfrac{\vec{\mu}_1 . \vec{\mu}_2 - 3(\vec{\mu}_1 . \vec{n})(\vec{\mu}_2 . \vec{n})}{4\pi\epsilon_0 R^3}$

Applications of Rydberg Atoms: many body effects, ultracold plasma, condensed matter, quantum information

M. Saffman et al , Rev. Mod. Phys. 82 2313 (2010);
D. Comparat and P. Pillet, JOSA B 27(6) A208 (2010)

Dipole Blockade

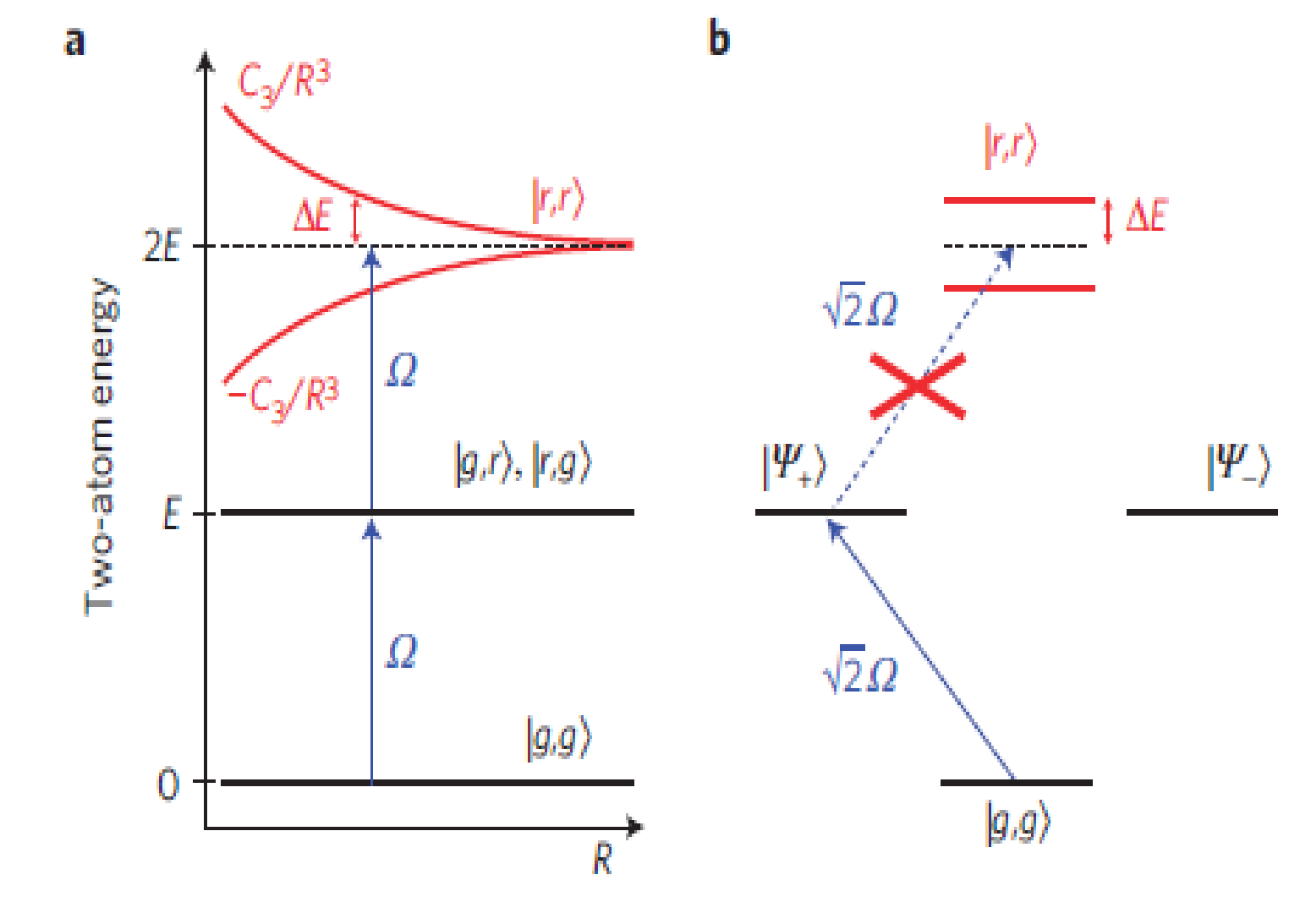
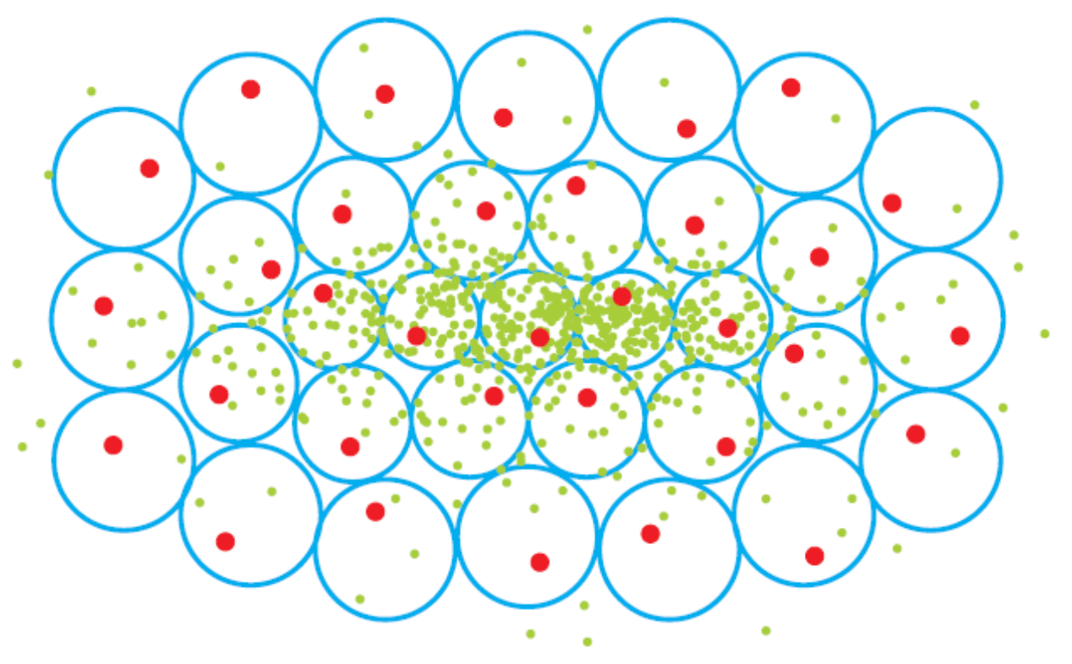


Figure 1 | Rydberg excitation of two atoms in the blockade regime.

In the phenomenon of dipole blockade (DB) the dipole-dipole (DD) interaction causes shifting of Rydberg states energy, which makes the applied laser off-resonant and results in effective 2-level systems [1].

A. Gaëtan et al. Nature Physics, 5 115 (2009)

Blockade Radius



In each "blockade sphere" with radius Rb the simultaneous excitation of two / multiple Rydberg atoms is suppressed.
Since the blockaded atoms Nb in the sphere are indistinguishable, they include an effective "superatom" and interact with the excitation light via collectively enhanced Rabi frequency.

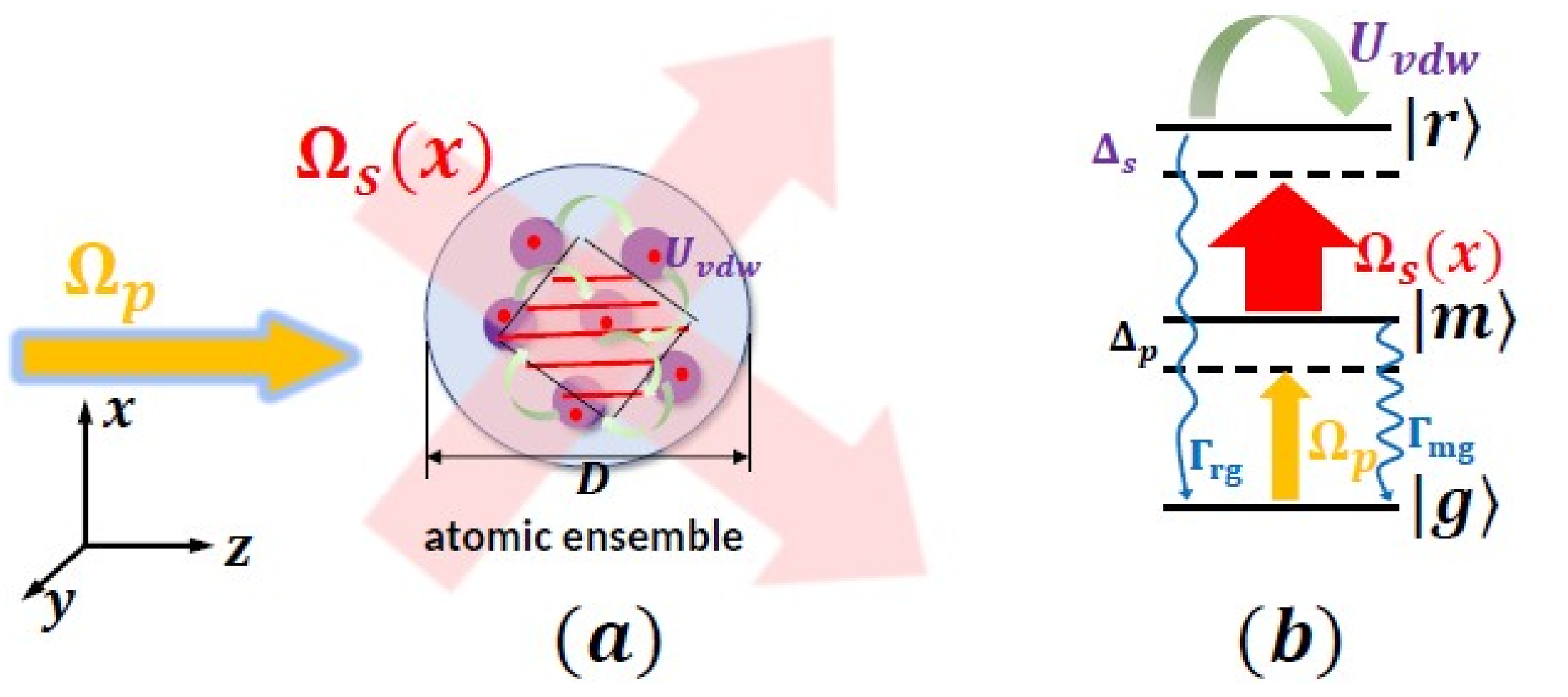
The DB occurs when the energy shift caused by the DD interaction becomes equal to the excitation linewidth, which gives the expression for the dipole blockade radius when there is only one atom in the sphere [2]:

$$R_b = (C_6/\omega)^{\frac{1}{6}}$$

where C_6 is the van der Waals (vdW) coefficient and ω is the spectral linewidth.

R. Löw et al, J. Phys. B: At. Mol. Opt. Phys. 45 113001, (2012)

Excitation scheme



We consider the case of two Rydberg atoms interacting via the van der Waals interaction in an Electromagnetically Induced Transparency (EIT) [3] scheme.
Each atom is in a three-level ladder conguration, where the ground |g> and middle |m>states are coupled by the probe field with Rabi frequency Ωp, while the |m> and the Rydberg state |ri> are connected via the coupling field Ωs.

Theoretical Model

The Hamiltonian of the system in the Rotating Wave Approximation is given by:

$$H = H_a + H_{af} + U_{vdW}$$

Ha: unperturbed atomic Hamiltonian
Haf: Atom-fields coupling
Uvdw: vdW interaction

With above Hamiltonian, we can derive the analytical expression for the steady state solution of the Rydberg level population [4] :

$$\boxed{\sigma_{rr} = \frac{\Omega_p{}^2[\Omega_p{}^2 + \Omega_s(x)^2]}{[\Omega_p{}^2 + \Omega_s(x)^2]^2 + 2\Delta_p(\Delta_s - s)\Omega_s(x)^2 + (\Delta_s - s)^2(\gamma_{gm}^2 + \Delta_p^2 + 2\Omega_p{}^2)}} \quad (1)$$

The coupling field is a standing wave , while the probe fiels is a travelling wave.

The parameter “s” describes the energy shift to the state |r> induced by the vdW interaction with other exciting atoms, which are usually situated beyond the blockade radius Rb.

$$\boxed{s = \frac{\omega}{\xi}\sigma_{rr} = \frac{\Omega_p{}^2 + \Omega_s(x)^2}{\xi\sqrt{\gamma_{gm}^2 + \Delta_p^2 + 2\Omega_p{}^2}} \frac{\Omega_p{}^2[\Omega_p{}^2 + \Omega_s(x)^2]}{[\Omega_p{}^2 + \Omega_s(x)^2]^2 + 2\Delta_p\Delta_s\Omega_s(x)^2 + \Delta_s{}^2(\gamma_{gm}^2 + \Delta_p^2 + 2\Omega_p{}^2)}} \quad (2)$$

The parameters $\xi = \left(\frac{R}{R_b}\right)^3$ is treated as an adjustable parameter controlled by the atomic density and a value of ξ > 1 means that the blockade is imperfect.

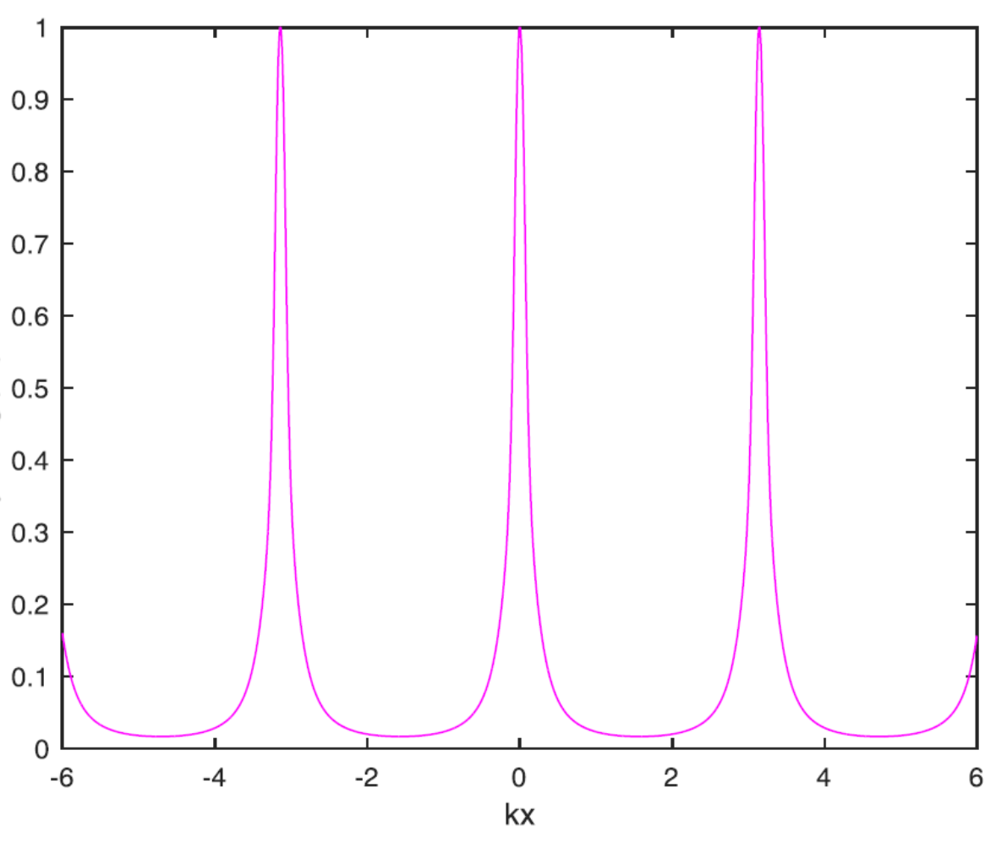
From Eqs. 1 and 2 follows that the we can achieve perfect localization

$\sigma_{rr} = 1$, when the condition $\Delta_s - s = 0$ holds at the nodes of the standing wave coupling field $\Omega_s = \Omega_{0s}\sin(kx)$.

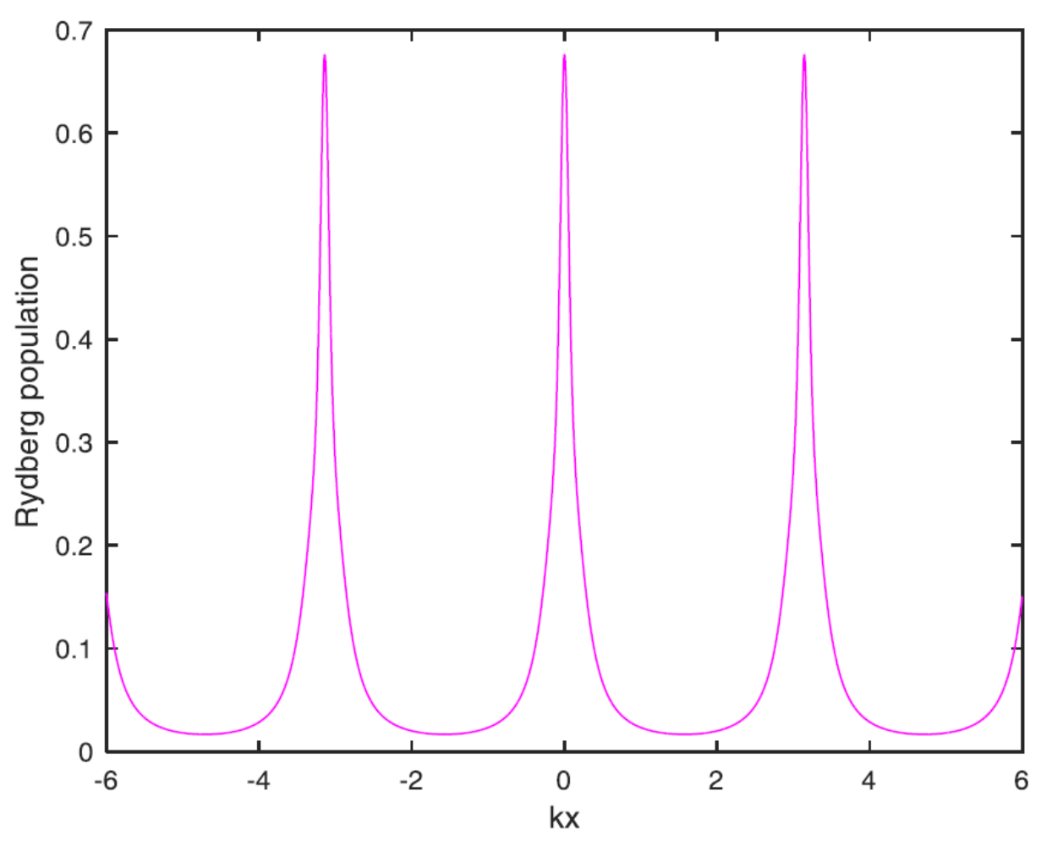
D. Ma et al. Phys. Rev. A 99,033826 (2019)

Atom Localization in 1D

The coupling field is a standing wave , while the probe field is a travelling wave :$\Omega_s = \Omega_{0s}\sin(kx)$.



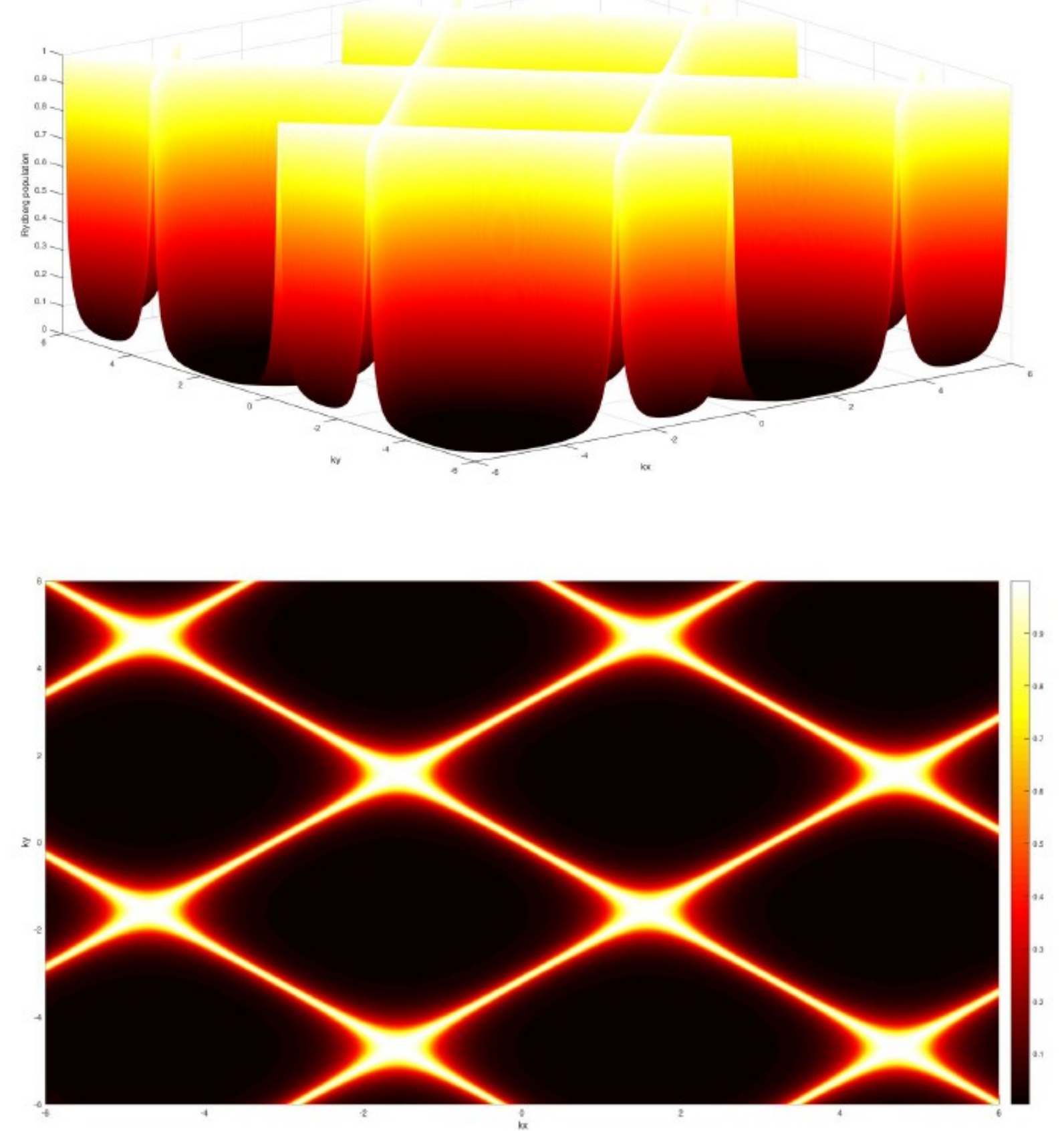
Population of Rydberg state as a function of kx with parameters:Ω_{0s}= 10, Ωp = 1.3, ξ= 0.3, Γgm = 1, Δp = 0, under the condition Δ_s- s=0 at the coupling field nodes.
The population of the Rydberg level reaches its maximal value of 1, meaning that a perfect atom localization [5] in 1D can be achieved.



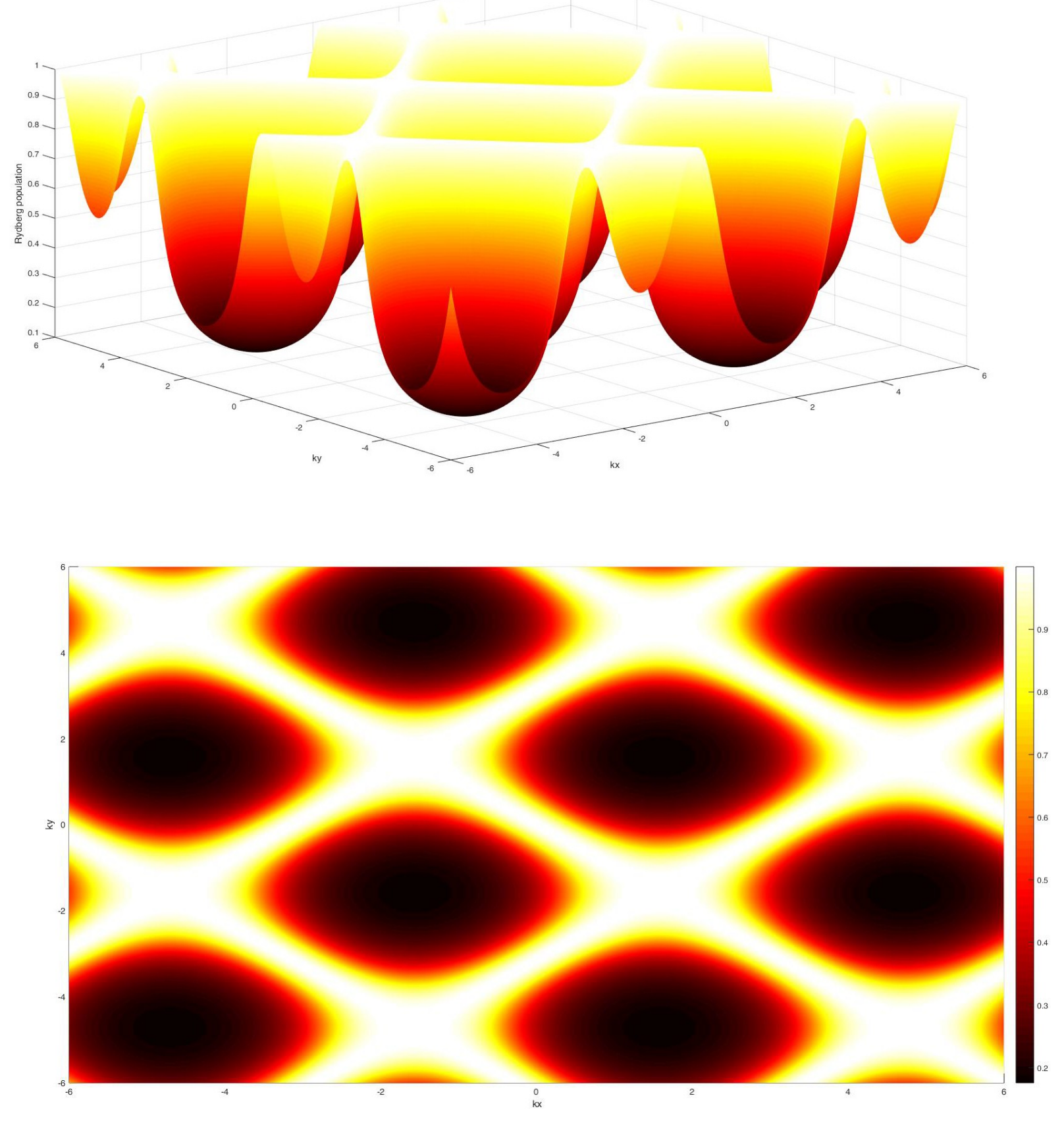
Population of Rydberg state as a function of kx with parameters:Ω_{0s}= 10, Ωp = 1.3, ξ= 0.3, Γgm = 1, Δp = 0, Δs = 0.8.
Once Δs deviates from the condition Δ_s- s=0 , the number of Rydberg atoms in the nodes of the standing wave decrease significantly.

Atom Localization in 2D

The coupling field is a standing wave , while the probe field is a travelling wave :$\Omega_s = \Omega_{0s}[\sin(kx)+\sin(ky)]$.



Population of Rydberg state as a function of kx and ky (surface and XY section)
With parameters:Ω_{0s}= 10, Ωp = 1.3, ξ= 0.3, Γgm = 1, Δp = 0, under the condition Δ_s- s=0 at the coupling field nodes.
The population of the Rydberg level reaches its maximal value of 1, meaning that a perfect atom localization in 2D can be achieved.



Population of Rydberg state as a function of kx and ky (surface and XY section)
With parameters:Ω_{0s}= 10, Ωp = 10, ξ= 0.3, Γgm = 1, Δp = 0, under the condition Δ_s- s=0 at the coupling field nodes.
The population of the Rydberg level reaches its maximal value of 1, meaning that a perfect atom localization in 2D can be achieved.
However, using a stronger probe field leads to widening of the spectral lines.

References:

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[2] D. Tong et al., Phys. Rev. Lett,93, 063001 (2004).
[3] S. Harris, *Electromagnetically Induced Transparency*, Physics Today, 50 (7), 36 (1997)
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[5] G. S. Agarwal and K. T.Kapale, J Phys B, 39 (17) (2006)

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