Transport and interaction blockade of cold bosonic atoms in a triple-well potential

Peter Schlagheck*, Francesc Malet, Jonas C. Cremon, and Stephanie M. Reimann

Division of Mathematical Physics, LTH, Lund University, Sweden

*Département de Physique, Université de Liège, Belgium

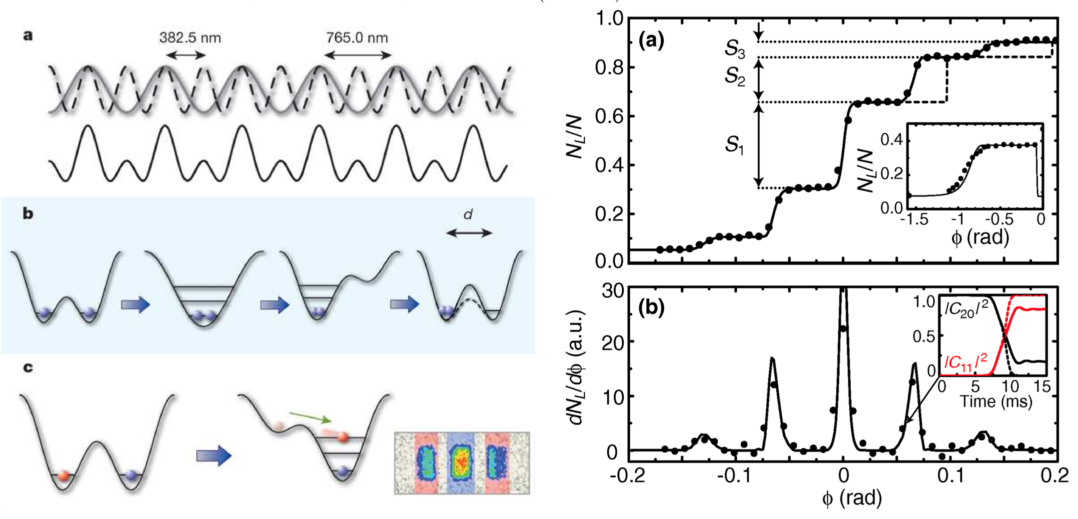
We investigate the transport properties of cold bosonic atoms in a triple-well potential that consists of two large outer wells, which act as microscopic source and drain reservoirs, and a small inner well, which represents a quantum-dot-like scattering region. Bias and gate "voltages" are introduced in order, respectively, to tilt the triple-well configuration and to shift the energetic level of the inner well with respect to the outer ones. By means of exact diagonalization considering a total number of 6 atoms in the triple-well potential, we find diamond-like structures for the occurrence of single-atom transport in the parameter space spanned by the bias and gate voltages, in close analogy with the Coulomb blockade in electronic quantum dots.

Motivation

Interaction blockade experiments in double-well superlattices created by two optical lattices with the wavelengths $\lambda_1 = 1530$ nm and $\lambda_2 = 0.5\lambda_1 = 765$ nm

S. Fölling et al., Nature 448, 1029 (2007)

P. Cheinet et al., PRL 101, 090404 (2008)

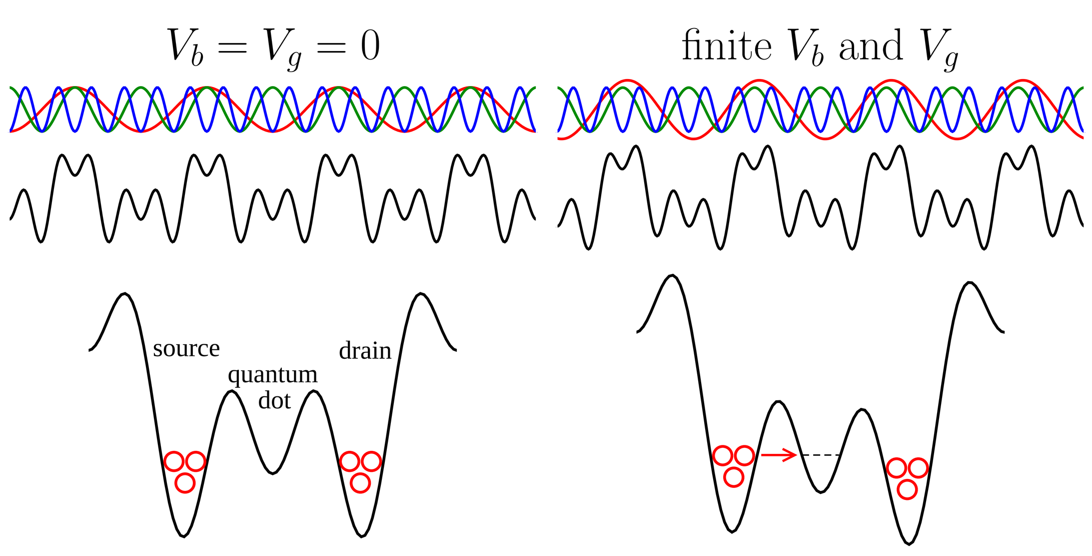


Triple-well lattice

$\longrightarrow$ add a third lattice with wavelength $\lambda_3 = 0.5\lambda_2$

Effective potential (for $k \equiv 4\pi/\lambda_1$):

$$V(x) = V_0[-\cos(kx) + \cos(2kx) - \cos(4kx)] \\ -V_g\cos(kx) - V_b\sin(kx)$$



V_b tilts the triple-well potentials: $\longrightarrow$ "bias voltage"

V_g pulls down the central well: $\longrightarrow$ "gate voltage"

$\longrightarrow$ analogy with Coulomb blockade for electrons:

- load the lattice at given gate voltage V_g and vanishing bias with a well-defined number of particles per triple-well site,
- ramp up the bias voltage until a given final value V_b,
- measure the populations in the left, central, and right wells.

Specifically we consider

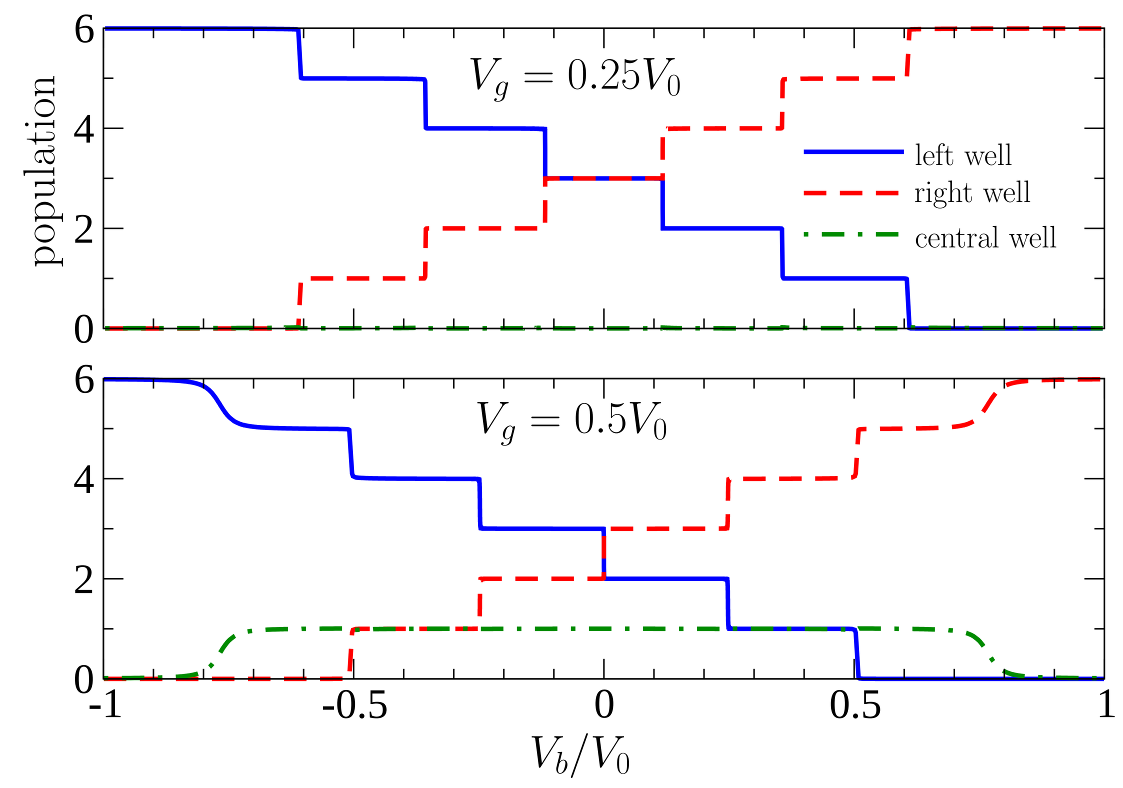
- ^{87}Rb atoms
- main periodicity $2\pi/k = \lambda_2 = 765$ nm
- main lattice strength $V_0 = 20\hbar^2k^2/m$
- effective 1D interaction strength $g = 4\hbar^2 k/m$

Ground-state populations

Exact numerical diagonalization (based on the Lanczos algorithm) of the many-body Hamiltonian

$$\hat{H} = \int dx \hat{\psi}^\dagger(x)\left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x)\right)\hat{\psi}(x) \\ + \frac{g}{2}\int dx \hat{\psi}^\dagger(x)\hat{\psi}^\dagger(x)\hat{\psi}(x)\hat{\psi}(x)$$

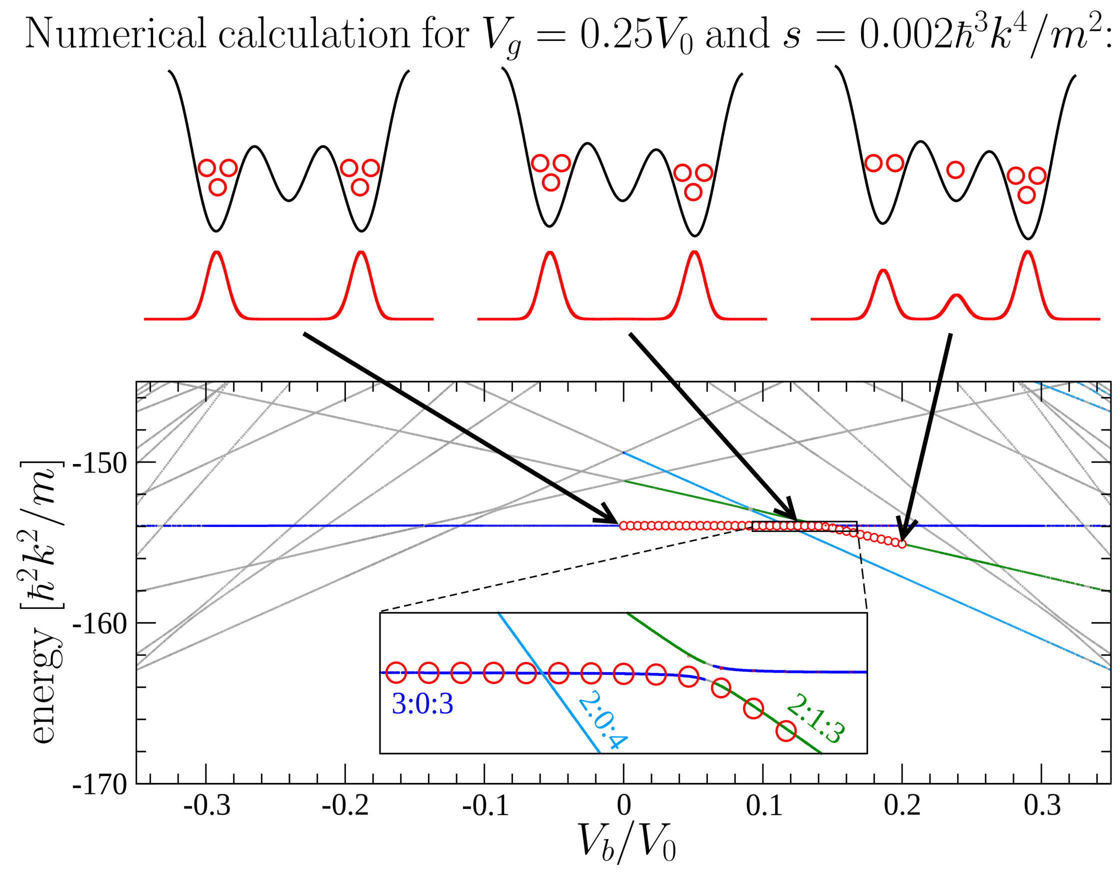
- assuming 6 atoms per triple-well site and
- neglecting hopping between adjacent triple-well sites ($\rightarrow$ periodic boundary conditions in x: $-\pi \leq kx \leq \pi$).



Single-atom transport

- prepare the lattice with 6 atoms per triple-well site,
- make the time-dependent ramping $V_b(t) = st$,
- decompose the time-dependent many-body wavefunction within the instantaneous eigenbasis.

Numerical calculation for $V_g = 0.25V_0$ and $s = 0.002\hbar^3k^4/m^2$:



Landau-Zener probability for nonadiabatic transitions at avoided crossings:

$$P = \exp[-2\pi\Delta E^2/(\hbar s)]$$

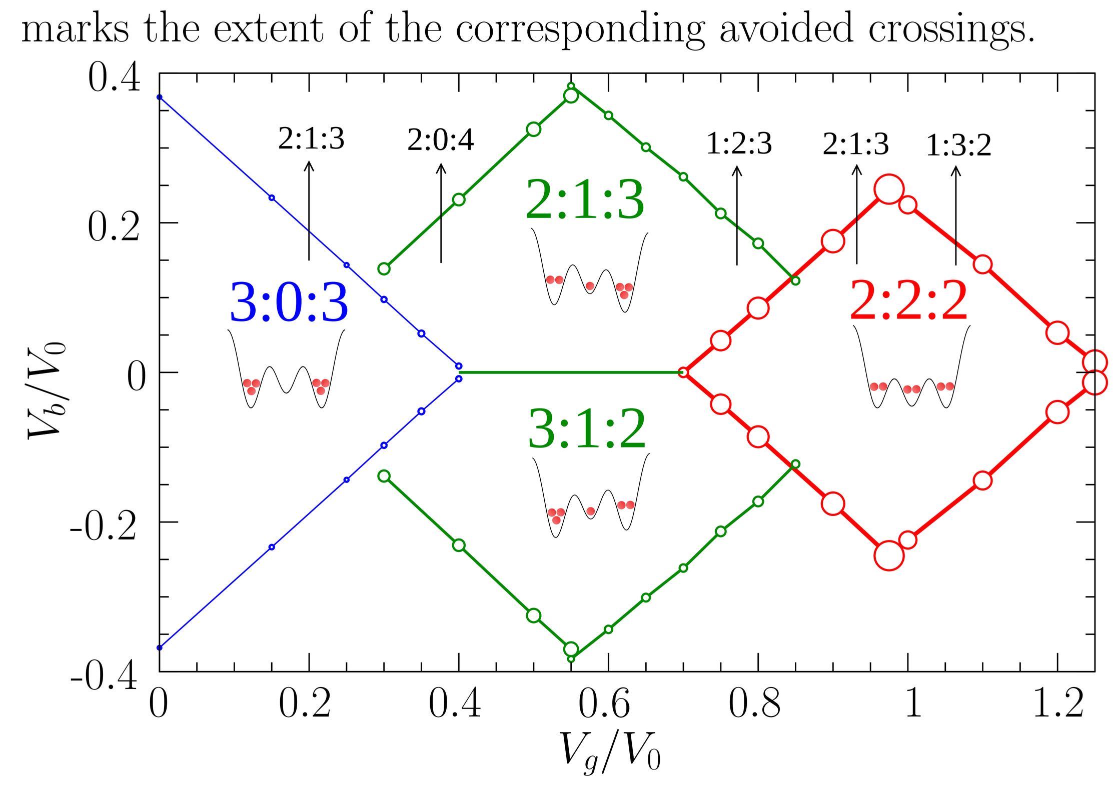
$\longrightarrow$ choose the ramping speed such that it is

- too fast for the unwanted anticrossings N_L:N_C:$N_R \leftrightarrow N_L \pm 1$:$N_C$:$N_R \mp 1$ with energy scale $\delta E \sim 0.001\hbar^2k^2/m$ for $N_C = 0$,
- but slow enough for the "good" anticrossings N_L:N_C:$N_R \leftrightarrow N_L \pm 1$:$N_C \mp 1$:$N_R$ or N_L:$N_C \pm 1$:$N_R \mp 1$ with energy scale $\Delta E \sim 10 \times \delta E$:

$$\delta E^2 \ll \hbar s < \Delta E^2$$

Atomic "Coulomb" diamonds

Plotted are the bias voltages V_b at which a single-atom transfer takes place between adjacent wells. The size of the circles marks the extent of the corresponding avoided crossings.



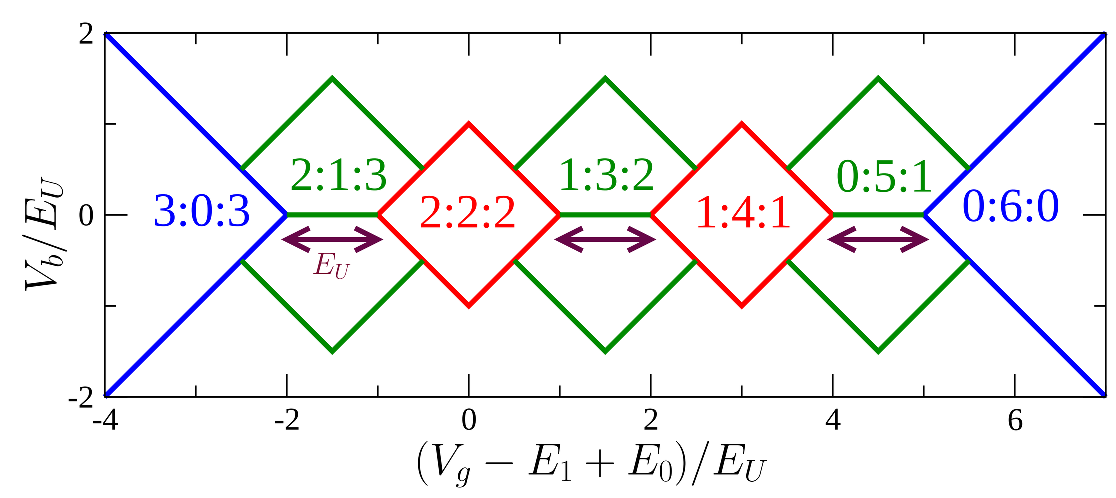
Bose-Hubbard model

Consider a simplified Bose-Hubbard model for the system with the on-site energies $E_{L/R} = E_0 \pm V_b$ and $E_C = E_1 - V_b$, with the local interaction energies $E_U^{(L/R/C)} = E_U \simeq 0.27V_0$, and with negligible tunnel coupling between adjacent wells.

Local particle-addition energies:
$\mu_{L/R}^{+} = E_0 \pm V_b + N_{L/R}E_U$ and $\mu_C^{+} = E_1 - V_b + N_C E_U$

$\longrightarrow$ avoided crossings of N_L:N_C:$N_R \leftrightarrow N_L \pm 1$:$N_C \mp 1$:$N_R$:
$V_b = E_1 - E_0 - V_g + (N_C - N_L \mp 1)E_U$

$\longrightarrow$ avoided crossings of N_L:N_C:$N_R \leftrightarrow N_L$:$N_C \pm 1$:$N_R \mp 1$:
$-V_b = E_1 - E_0 - V_g + (N_C - N_R \pm 1)E_U$



Main differences to Coulomb diamonds in quantum dots:

- open ends for empty dot and empty reservoirs
- asymmetry between balanced ($N_L = N_R$) and unbalanced ($N_L = N_R \pm 1$) populations in the reservoirs

$\longrightarrow$ microscopic nature of the reservoirs

Perspectives

$\rightarrow$ extract local interaction energy E_U from the distance between the diamond structures

$\rightarrow$ single-atom pumping (3:0:3 $\rightarrow$ 2:0:4) following a closed curve in $V_g - V_b$ space

$\rightarrow$ atomic transistors

P. Schlagheck, F. Malet, J. C. Cremon, and S. M. Reimann, New J. Phys., in press (arXiv:0912.0484)