Position-dependent spin-orbit coupling for ultracold atoms

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Recently several schemes have been proposed to create the spin-orbit coupling (SOC) of the Rashba-Dresselhaus type for ultracold atoms by illuminating them with several laser beams [1-3]. This leads to a number of distinct phenomena, such as formation of non-conventional Bose-Einstein condensates (BECs) of ultracold atoms affected by the SOC [2-4]. Here we explore effects due to the position-dependence of the SOC for atomic BECs. The position-dependence provides domains of the stripe phases with the stripes oriented in different directions. It is shown that non-trivial structures can be formed at the boundaries of these domains, such as defects or arrays of vortices and anti-vortices.

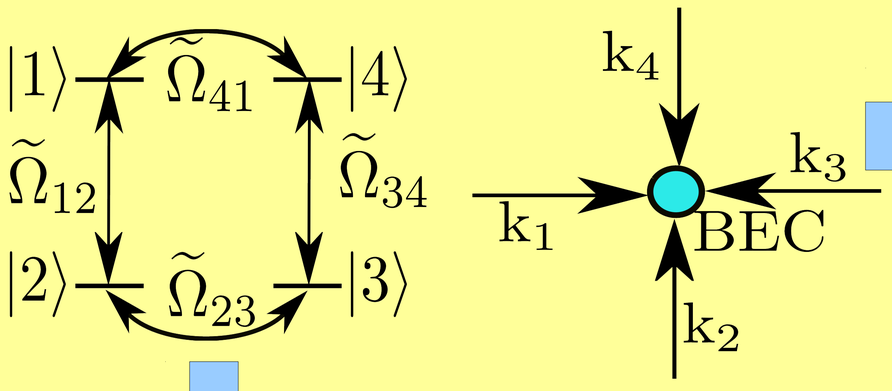
[1] J. Dalibard, F. Gerbier, G.Juzeliunas, and P.Ohberg, Artificial gauge potentials for neutral atoms. Rev. Mod. Phys. 83, 1523 (2011).
[2] N. Goldman, G. Juzeliunas, P. Ohberg, and I. B. Spielman, Light-induced gauge fields for ultracold atoms, Rep. Prog. Phys. 77 126401 (2014).
[3] V. Galitski and I. B. Spielman, Spin–orbit coupling in quantum gases, Nature 494, 49 (2013).
[4] H. Zhai, Degenerate Quantum Gases with Spin-Orbit Coupling, Rep. Prog. Phys. 78 026001 (2015).

Previous studies: SOC position independent (α_x, α_y = const)
D. L. Campbell, G. Juzeliūnas and I. B. Spielman, Phys. Rev. A 84, 025602 (2011).

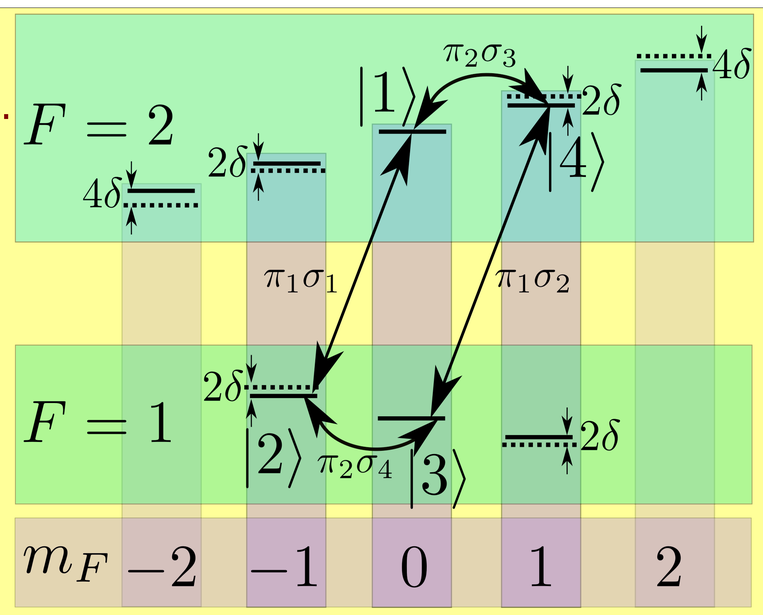
Here: Effects due to position dependence of α_x and α_y.
S.-W. Su, S.-C. Gou, I.-K. Liu, I. B. Spielman, L. Santos, A. Acus, A. Mekys, J. Ruseckas, and G. Juzeliūnas, New. J. Phys. 17, 033045 (2015).

A closed loop scheme to produce position dependent 2D SOC using **Raman** transitions.

$$\Omega_{j,j+1} = \Omega \exp\left[i\left(\mathbf{k}_j - \mathbf{k}_{j+1}\right)\cdot\mathbf{r} + \frac{\pi}{4}\right]$$

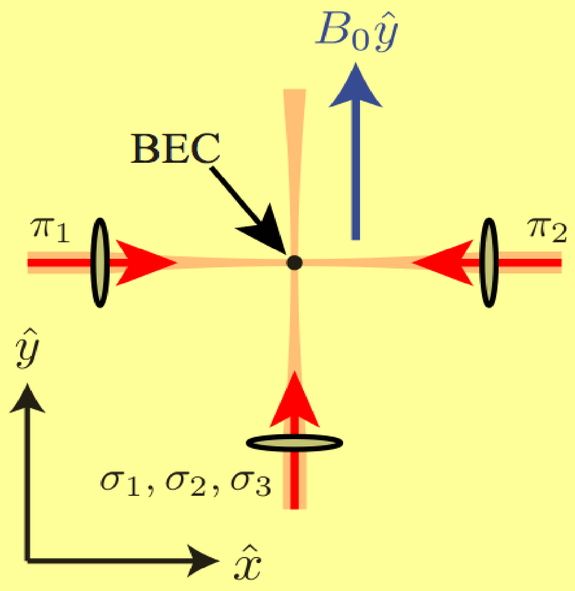


A pair of degenerate atomic dressed states



Position dependence of SOC due to position dependent detuning δ .

Laser beams layout



Rashba-Dresselhaus Spin-Orbit Coupling (SOC)

$$H = \frac{(\mathbf{p}-\mathbf{A})^2}{2m} = \frac{p^2}{2m} + \frac{\mathbf{p}\bullet\mathbf{A}}{2m} + const \qquad \mathbf{p} = -i\hbar\nabla$$

- Vector potential **A** – 2x2 matix: (2D SOC)

$$\mathbf{A} = \chi\left(\alpha_x\sigma_x\mathbf{e}_x + \alpha_y\sigma_y\mathbf{e}_y\right)$$

- σ_x, σ_y- Pauli matrices;
- H acts on a two-component spinor: $\psi = \begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}$

Asymmetric SOC:

$$\alpha_x = 1 + \delta/\Omega$$
$$\alpha_y = 1 - \delta/\Omega$$

Position dependent detuning

$\delta \equiv \delta(\mathbf{r})$ because of inhomogeneous magnetic field

⇒ position dependent SOC

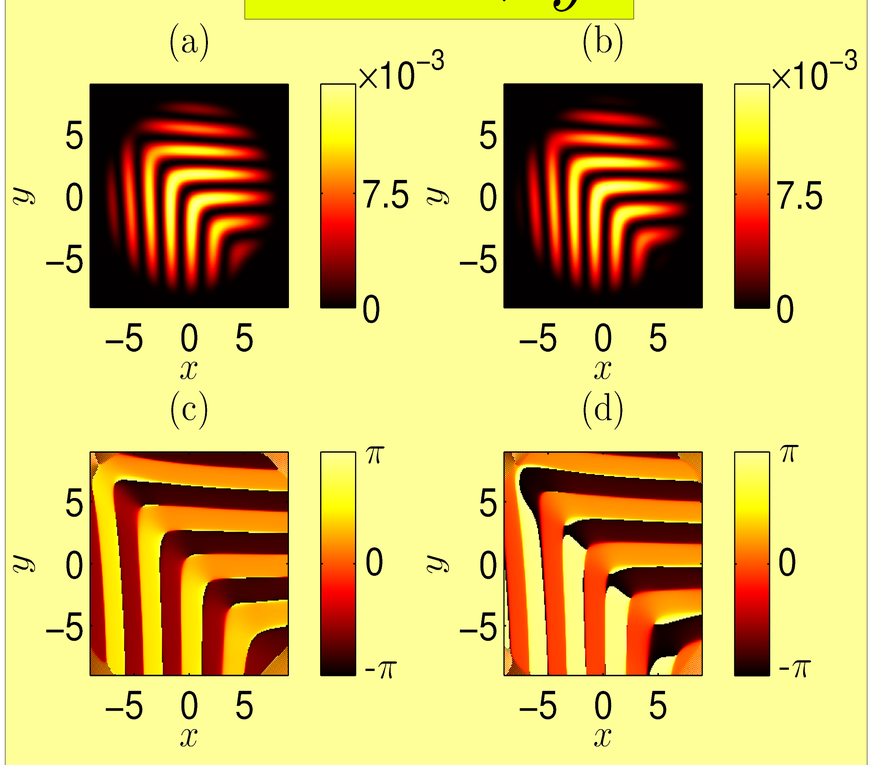
We consider:

Atomic BEC

Solution of the Gross-Pitaevskii equation with position dependent SOC.

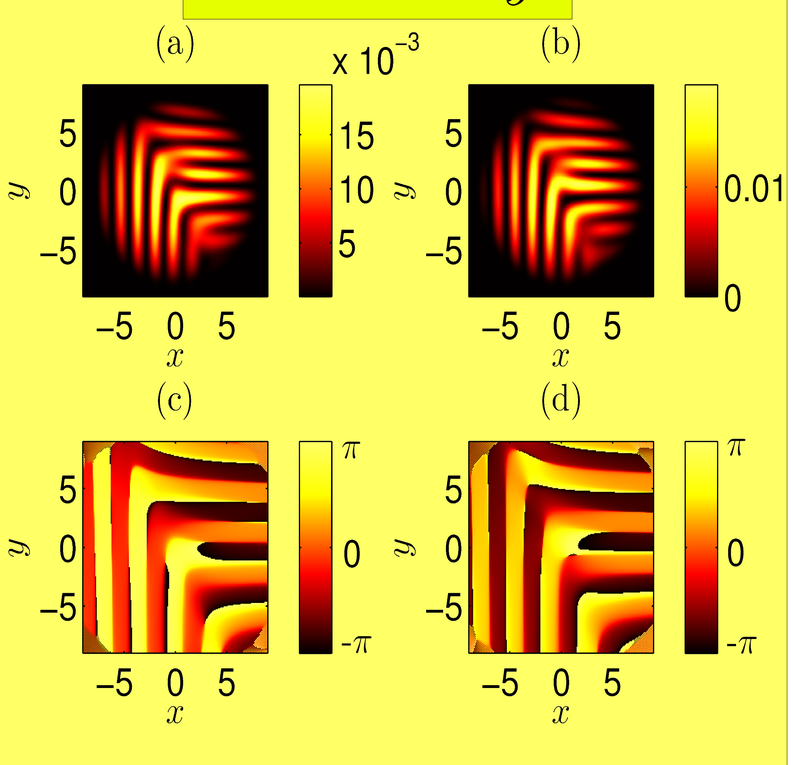
Atomic BEC affected by position dependent SOC

$\delta \sim x + y$



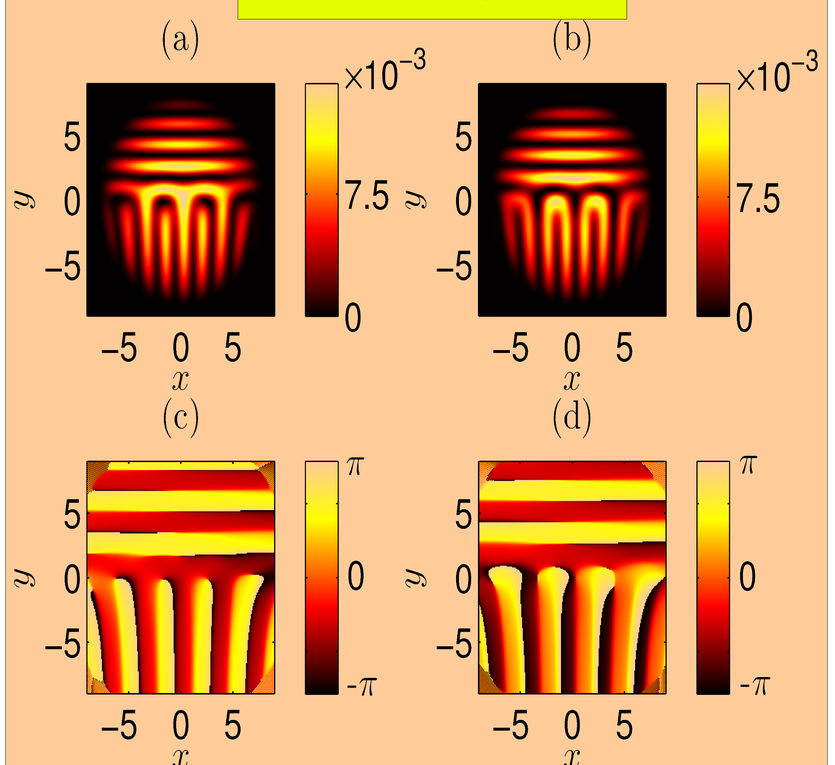
Matching stripes. Smooth transition between the stripes at the interface.

$\delta \sim x + 2y$



Non-matching stripes.
Defects / vortices at the interface.

$\delta \sim y$



Orthogonal stripes. Array of vortices at the interface.

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