Ultracold atoms carrying orbital angular momentum in sided coupled cylindrically symmetric potentials

Verònica Ahufinger

J. Polo, J. Mompart and V. A., Phys. Rev. A **93**, 033613 (2016)

G. Pelegrí, J.Polo, A. Turpin, M. Lewenstein, J. Mompart, V. A., Phys. Rev. A **95**, 013614 (2017)

Quantum Atom Optics
Grup d'Òptica UAB

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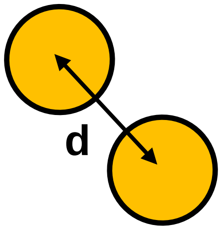
Universitat Autònoma de Barcelona

Introduction

Tunneling dynamics



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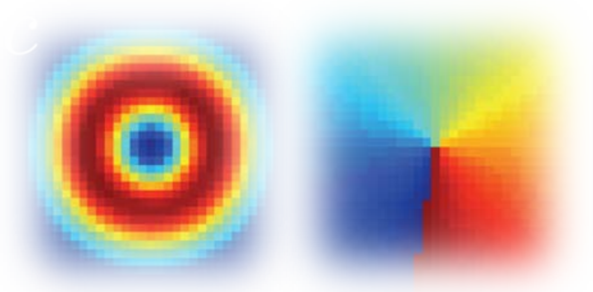
Orbital angular momentum

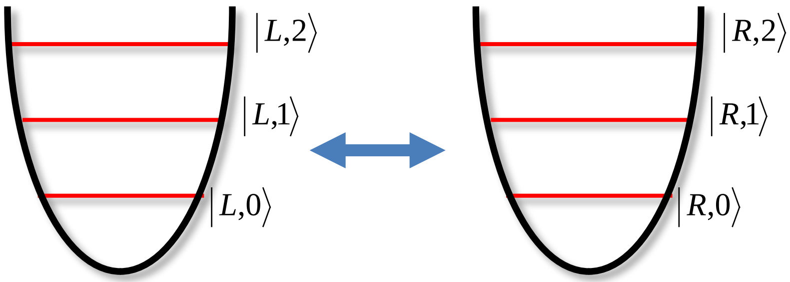


Outline

- Geometrically induced complex tunneling
  - Introduction
  - Two in-line ring potentials
  - Three ring potentials in a triangular configuration
  - Geometrically engineered spatial dark states
- Edge-like states in an optical ribbon
  - Optical ribbon
  - Ground state manifold
  - OAM manifold
  - Robustness
- Conclusions

Introduction

Tunneling amplitudes between two traps in 1D ⇨ Real



$$J^{k,p}_{j,n} \equiv \langle k,p|H|j,n\rangle = \int_{-\infty}^{+\infty} \psi^{*}_{k,p}(x) H \psi_{j,n}(x)\,dx$$

$j.k=L,R$

Tunneling amplitudes between two traps in 2D for OAM states?

Cylindrical symmetry:

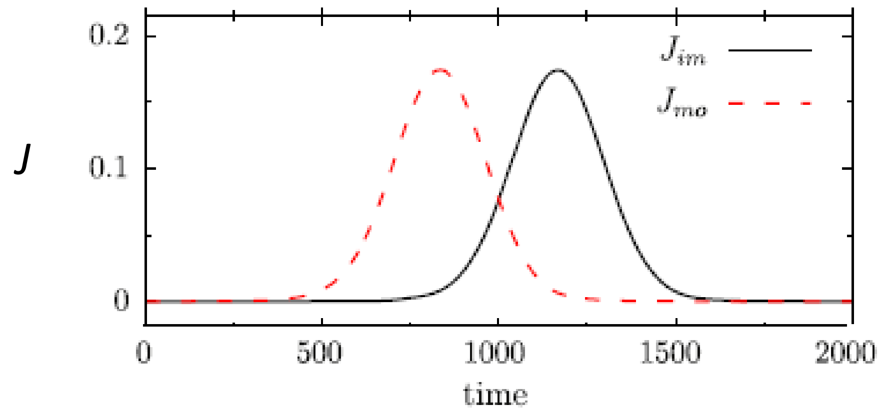
⇩ **Real**

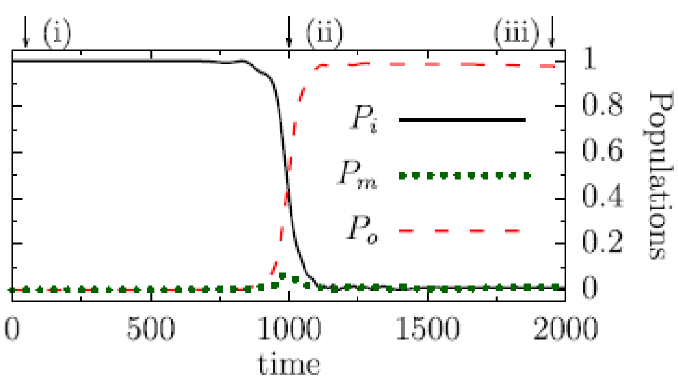
J. Polo *et al*., New Journal of Physics **18**, 015010 (2016)
J. Brand *et al*., Phys. Rev. A **80**, 011602 (2009)

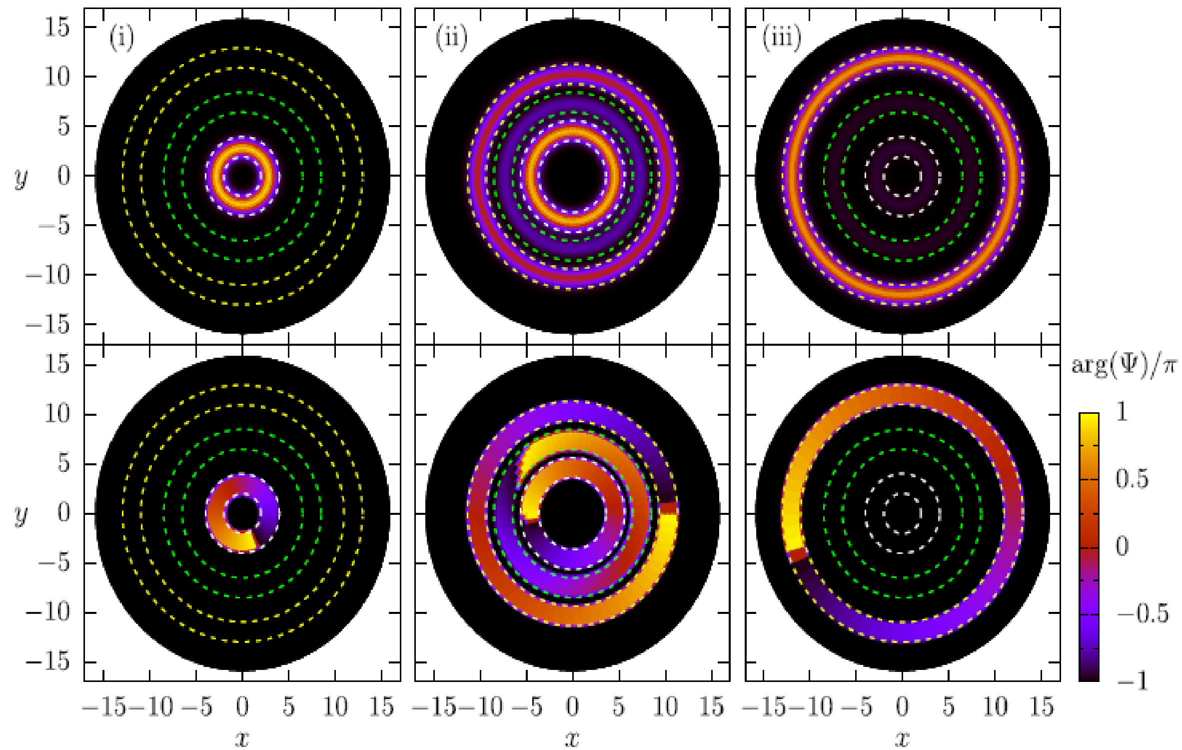
Introduction

J. Polo, A. Benseny, T. Busch, V. Ahufinger, J. Mompart, New Journal of Physics **18**, 015010 (2016)

Review on Spatial Adiabatic passage:
R. Menchon-Enrich A. Benseny, V. Ahufinger, A. D. Greentree, T. Busch, J. Mompart, Reports on Progress in Physics **79**, 074401 (2016)

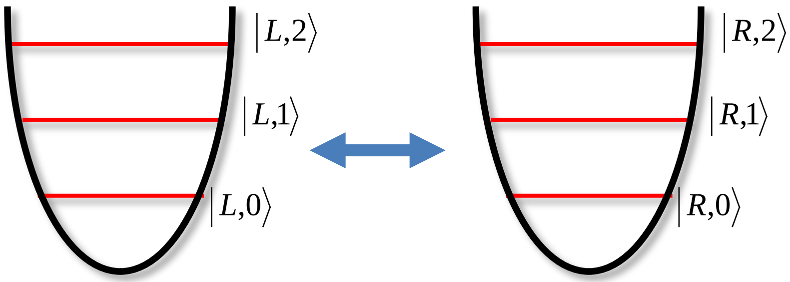






Introduction

Tunneling amplitudes between two traps in 1D → Real



$$J_{j,n}^{k,p} \equiv \langle k,p|H|j,n\rangle = \int_{-\infty}^{+\infty} \psi_{k,p}^{*}(x) H \psi_{j,n}(x) dx$$

$j.k = L,R$

Tunneling amplitudes between two traps in 2D for OAM states?

Cylindrical symmetry:

Real

J. Polo *et al*., New Journal of Physics **18**, 015010 (2016)
J. Brand *et al*., Phys. Rev. A **80**, 011602 (2009)

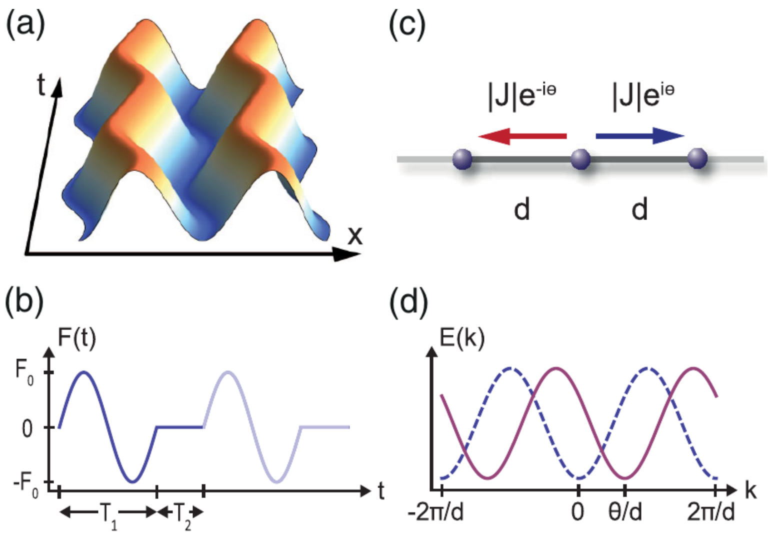
I. Lesanovsky and W. von Klitzing, Phys. Rev. Lett. **98**, 050401 (2007)
J. Brand *et al*., Phys. Rev. A **81**, 025602 (2010)
L. Amico *et al*., Scientific Reports **4**, 4298 (2013)

Breaking the cylindrical symmetry with more than two traps → Complex

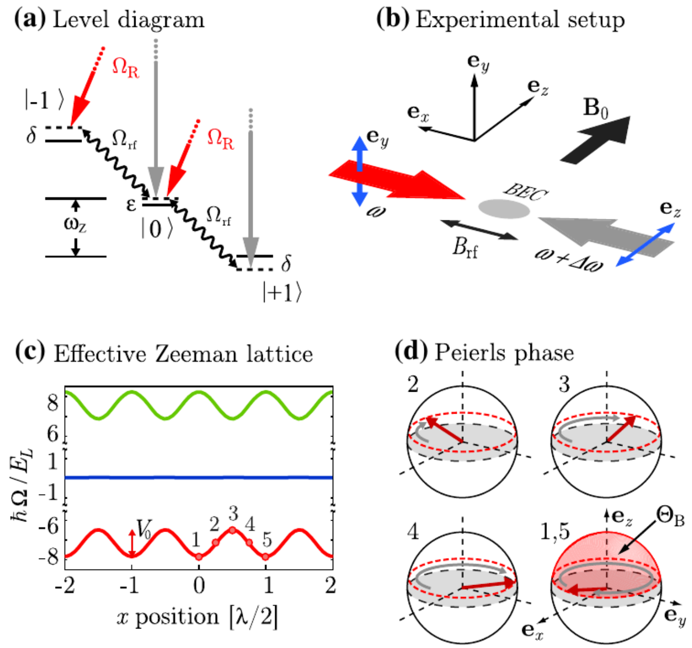
Introduction

How to create complex tunnelings?

Suitable forcing of the optical lattice
P. Windpassinger *et al*., Phys. Rev. Lett. **108**,225304 (2012)



Combination of radio frequency and Raman fields that couple to the internal states of the atom
I.B.Spielman *et al*., Phys. Rev. Lett. **108**,225303(2012)



Geometrically induced complex tunneling through orbital angular momentum states. J.Polo,J.Mompart,V.Ahufinger, Phys. Rev. A **93**, 033613 (2016)

Introduction

Interest of complex tunnelings?

- Generation of artificial vector gauge potentials

  J. Dalibard *et al.*, Rev. Mod. Phys. **83**, 1523 (2011)

- Generation of staggered fluxes

  I. Bloch *et al.*, Phys. Rev. Lett. **107**,255301 (2011)

  L. Mathey *et al.*, Nature Physics **9**,738 (2013)

- Implementation of the Hofstadter, Harper and Weyl Hamiltonians

  I. Bloch *et al.*, Phys. Rev. Lett. **111**,185301(2013)

  W.Ketterle *et al.*, Phys. Rev. Lett. **111**,185302(2013)

- Realization of the topological Haldane model

  T. Esslinger *et al.*, Nature **515**,237(2014)

- Geometrical engineering of spatial dark states

  J.Polo, J.Mompart, V.Ahufinger, Phys. Rev. A **93**, 033613 (2016)

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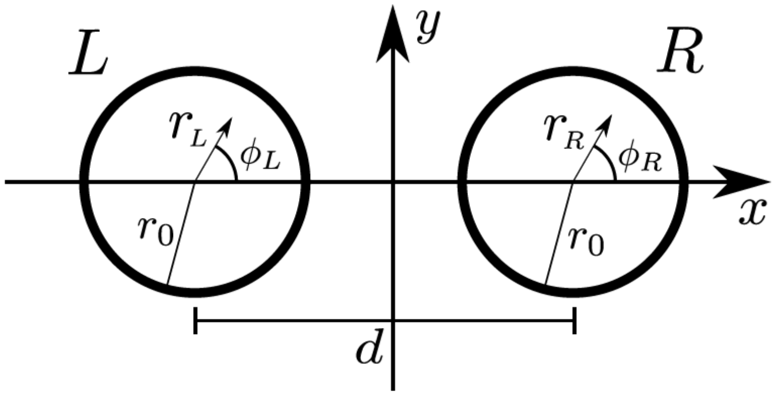
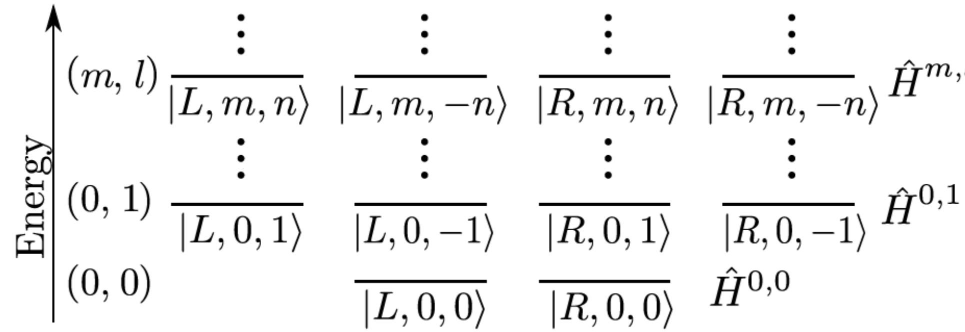
Two in-line ring potentials





$l = |n|$

winding number, $n=\pm l$, l being the orbital angular momentum quantum number

$$\Psi^{n}_{j,m}(r_j, \phi_j) = \langle \vec{r} | j, m, n \rangle = \frac{1}{\sqrt{N}} \psi_m(r_j) e^{in(\phi_j - \phi_0)}$$

azimutal phase origin

$j=R,L$ transverse vibrational state

radial part

Assuming $\sigma_m \ll r_0 \ll d$

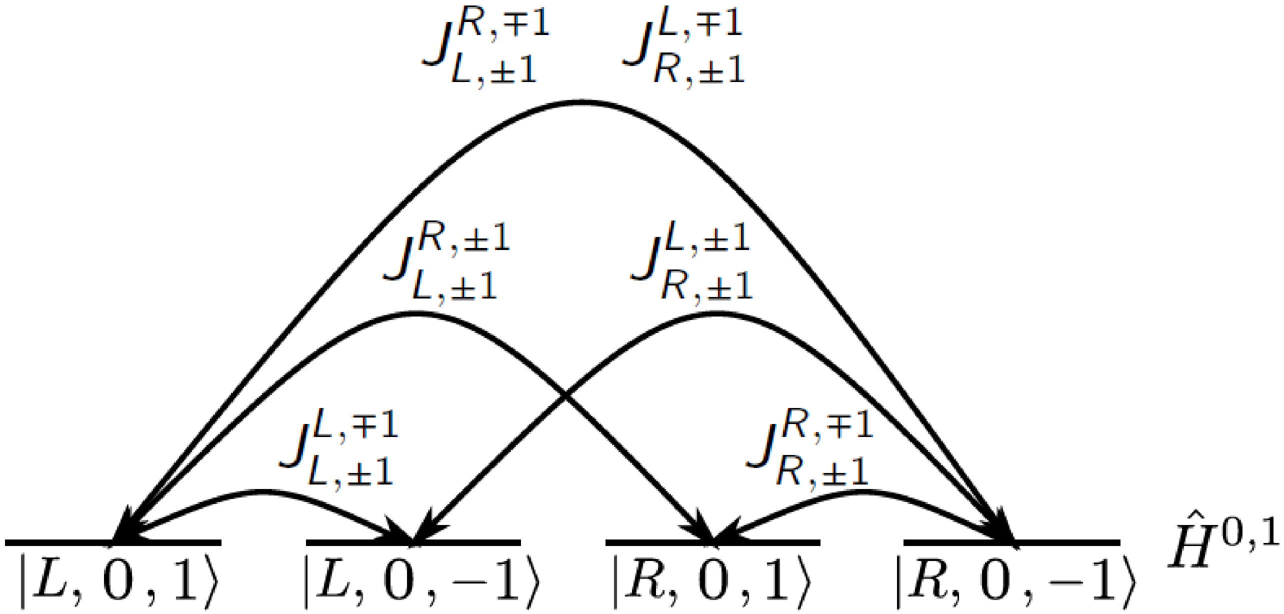
$$\hat{H}_T = \sum_{m\geq 0} \hat{H}^{m,0} + \sum_{m\geq 0} \sum_{l>0} \hat{H}^{m,l}$$

Two in-line ring potentials

$$\hat{H}^{m,l} = \frac{\hbar}{2} \sum_{j,k=L,R} \sum_{n=\pm l} \left(J_{j,n}^{k,n}(m)|j,m,n\rangle\langle k,m,n| + J_{j,n}^{k,-n}(m)|j,m,n\rangle\langle k,m,-n| \right)$$

$\frac{\hbar}{2} J_{j,n}^{j,n}(m)$ →	eigenenergies of a single atom →	They define the origin of energy
$J_{j,n}^{j,-n}(m)$ →	self-coupling →	Couples states within the same ring. Appears due to the breaking of the cylindrical symmetry of the system
$J_{j,n}^{k,-n}(m)$, $J_{j,n}^{k,n}(m)$ →	cross-coupling (with $j \neq k$) →	Couplings between states at different rings

Two in-line ring potentials



$$\hat{H}^{m,l} = \frac{\hbar}{2}\begin{pmatrix} 0 & J^{L,-n}_{L,n} & J^{R,n}_{L,n} & J^{R,-n}_{L,n} \\ J^{L,n}_{L,-n} & 0 & J^{R,n}_{L,-n} & J^{R,-n}_{L,-n} \\ J^{L,n}_{R,n} & J^{L,-n}_{R,n} & 0 & J^{R,-n}_{R,n} \\ J^{L,n}_{R,-n} & J^{L,-n}_{R,-n} & J^{R,n}_{R,-n} & 0 \end{pmatrix}$$

$$|L,0,+1\rangle = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Two in-line ring potentials

Hermiticity of the Hamiltonian $J_{j,n}^{k,p} = \left(J_{k,p}^{j,n}\right)^*$ ⟶ Six independent couplings

Symmetries $[\hat{H}, \hat{M}_x] = [\hat{H}, \hat{M}_y] = 0$

$$J_{j,n}^{k,p} = \langle k,p|\hat{H}|j,n\rangle = \langle k,p|\hat{M}_y^{-1}\hat{H}\hat{M}_y|j,n\rangle = \langle k,p|\hat{M}_x^{-1}\hat{H}\hat{M}_x|j,n\rangle$$

$$(x,\ y) \xrightarrow{\hat{M}_x} (x,\ -y) \longrightarrow \hat{M}_x|j,m,n\rangle = e^{-2in\phi_0}|j,m,-n\rangle$$

$$(x,\ y) \xrightarrow{\hat{M}_y} (-x,\ y) \longrightarrow \hat{M}_y|j,m,n\rangle = e^{-2in\phi_0}e^{in\pi}|k,m,-n\rangle \text{ for } j \neq k$$

$$J_{L,n}^{L,-n} = |J_{L,n}^{L,-n}|e^{2in\phi_0}$$

$$J_{L,n}^{R,n}$$

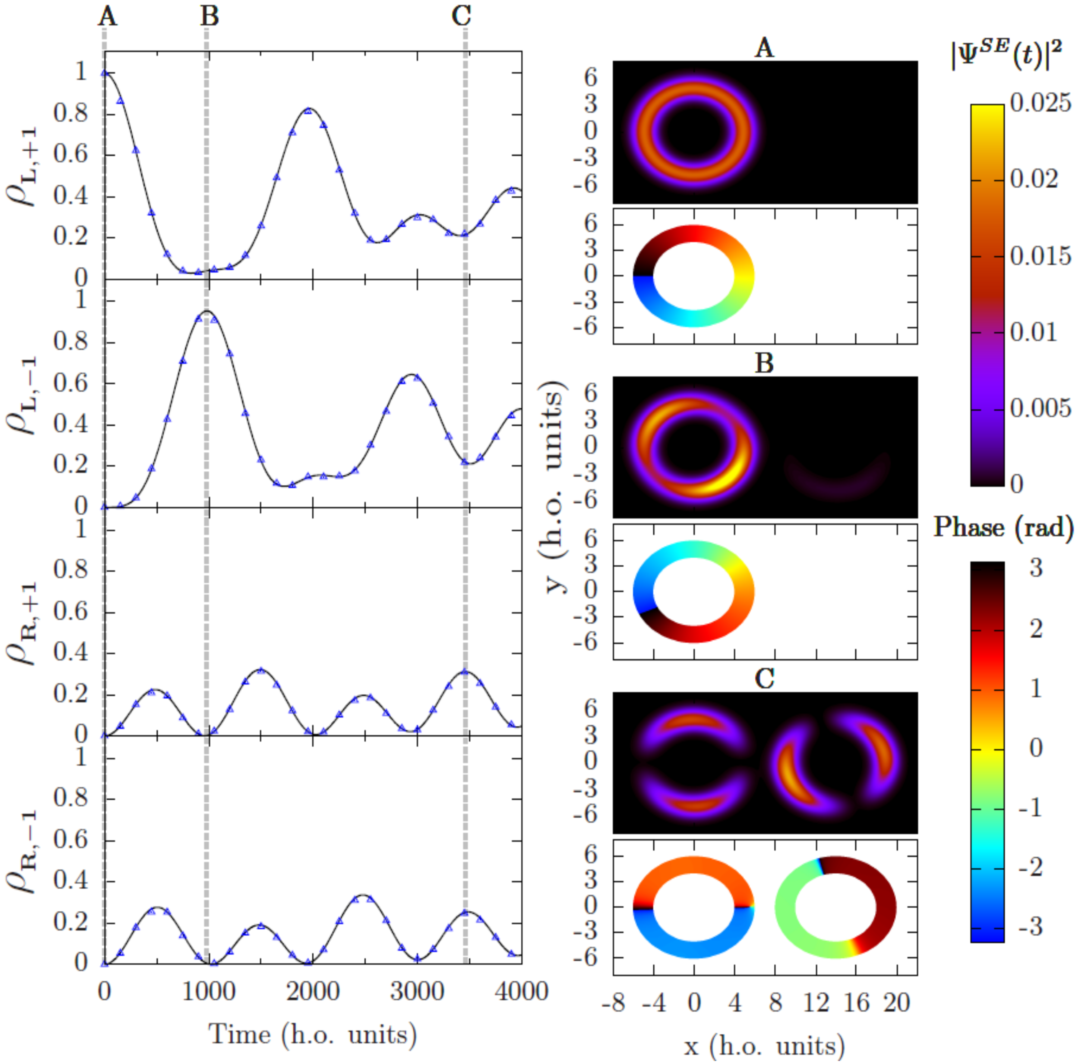
$$J_{L,n}^{R,-n} = |J_{L,n}^{R,-n}|e^{2in\phi_0}$$

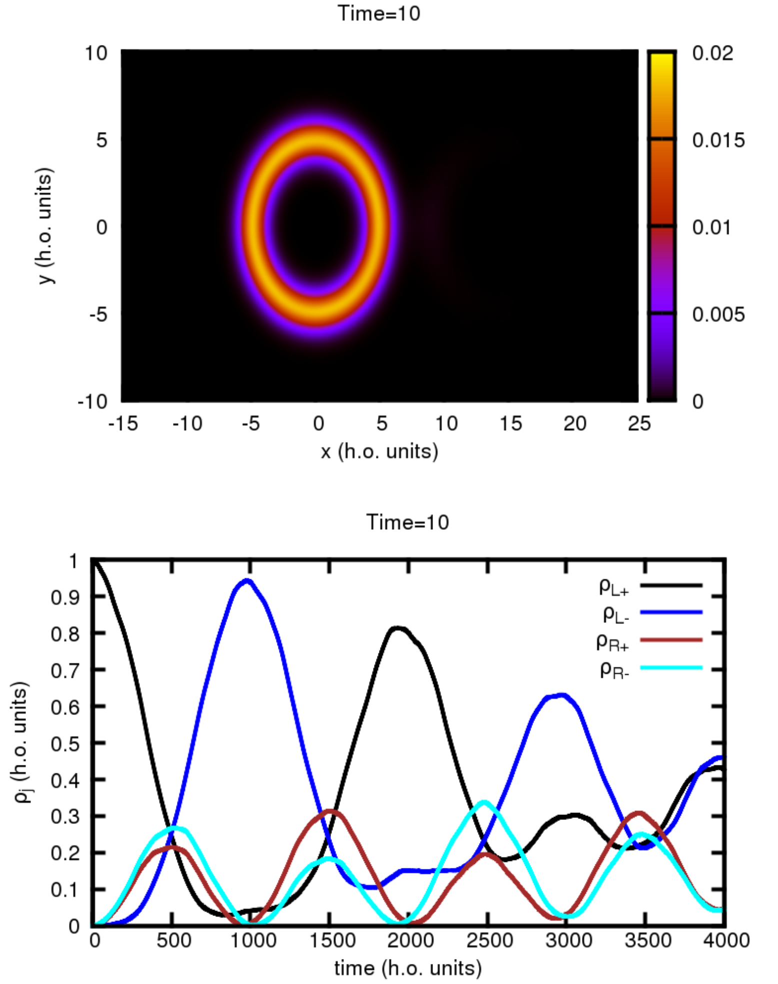
⟹

$$\hat{H}^{m,l} = \frac{\hbar}{2}\begin{pmatrix} 0 & J_{L,n}^{L,-n} & J_{L,n}^{R,n} & J_{L,n}^{R,-n} \\ J_{L,-n}^{L,n} & 0 & J_{L,-n}^{R,n} & J_{L,-n}^{R,-n} \\ J_{R,n}^{L,n} & J_{R,n}^{L,-n} & 0 & J_{R,n}^{R,-n} \\ J_{R,-n}^{L,n} & J_{R,-n}^{L,-n} & J_{R,-n}^{R,n} & 0 \end{pmatrix}$$

$\phi_0 = 0$

Two in-line ring potentials





r_0=5
d=14

and $J_{L,1}^{R,1} = 3.06 \times 10^{-3}$ $J_{L,1}^{R,-1} = 3.28 \times 10^{-3}$
$J_{L,1}^{L,-1} = -4.06 \times 10^{-4}$ in h.o. units

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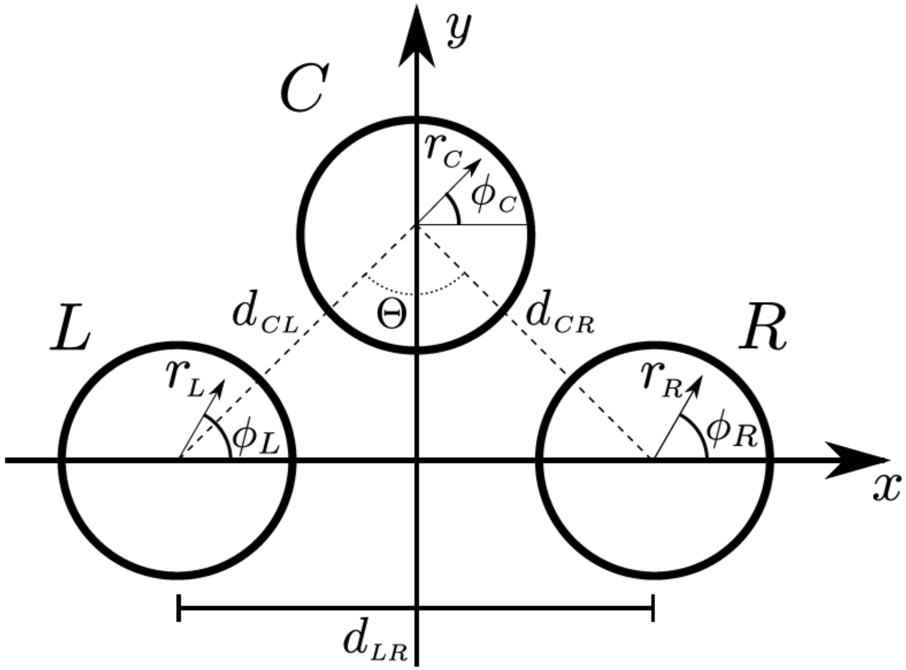
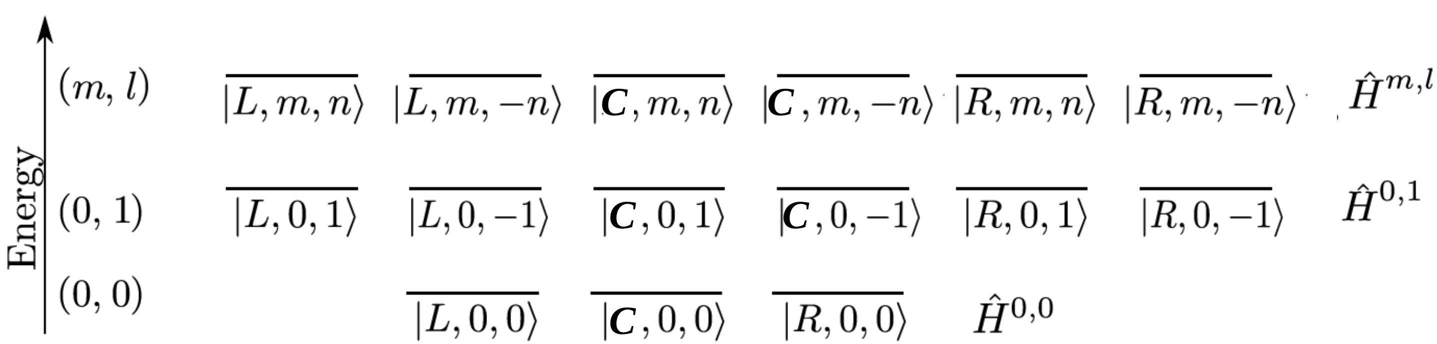
Triangular configuration

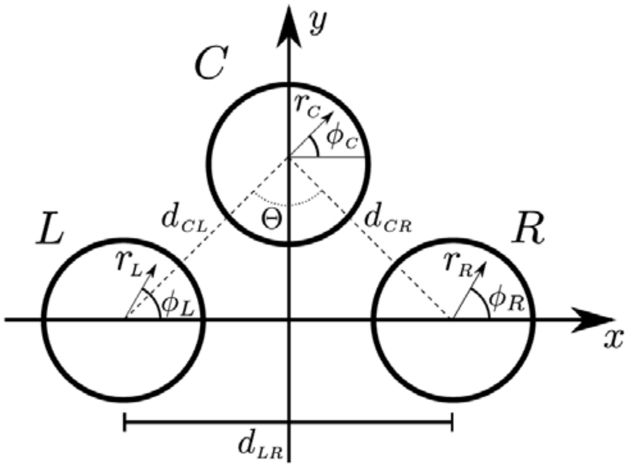




Triangular configuration

$d_{CL} = d_{CR} \equiv d$ and $d_{LR} = 2d\sin(\Theta/2)$

Assumptions: left and right rings are decoupled, i.e., $d_{LR} \gg d$



$\phi_0 = 0$ C-L axis

→ C-L couplings → $\left.\begin{array}{l} J_1 \\ J_2 \\ J_3 \end{array}\right\} \in \mathbb{R}$

→ C-R couplings → $\left.\begin{array}{l} J_1 \\ J_2 \\ J_3 \end{array}\right\} \in \mathbb{C}$

$$J_{C,n}^{C,-n} = J_{L,+n}^{L,-n}(1 + e^{2in\Theta})$$

For $n\Theta = \pi/2$ → $J_{C,n}^{C,-n} = 0$

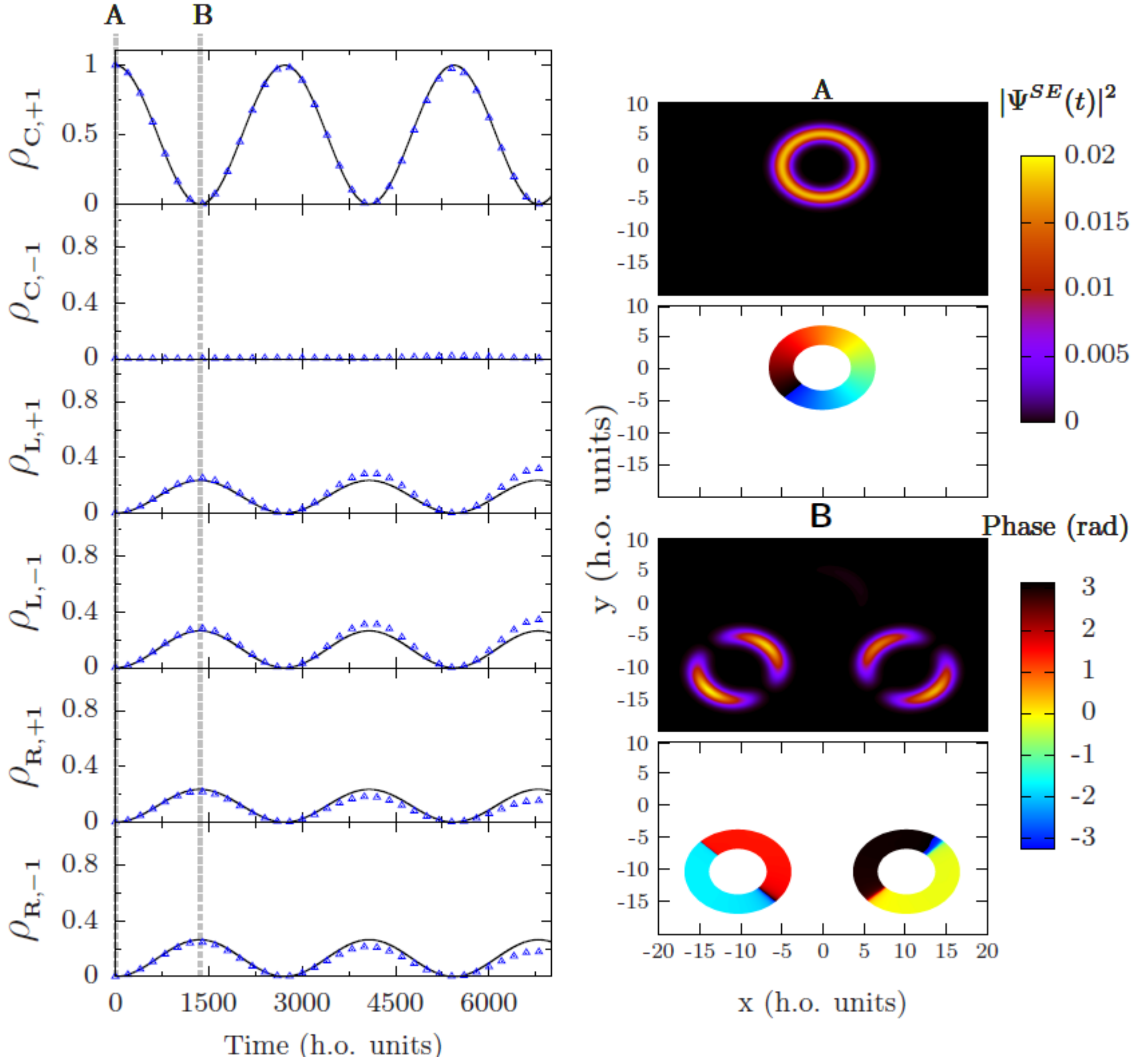
where $J_1 = J_{L,n}^{L,-n}$

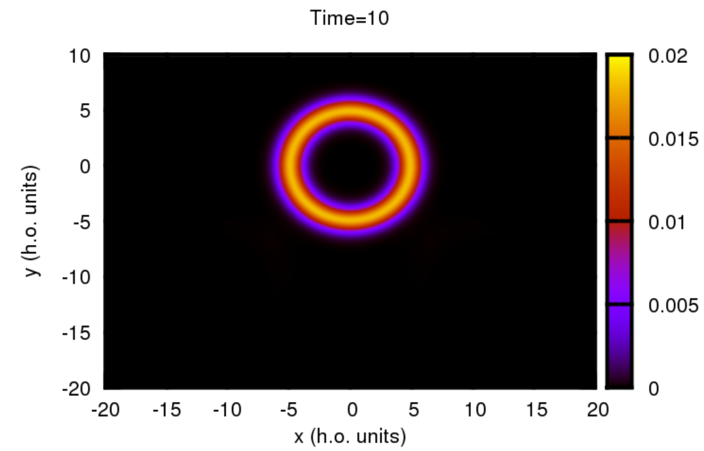
$J_2 = J_{L,n}^{C,n}$

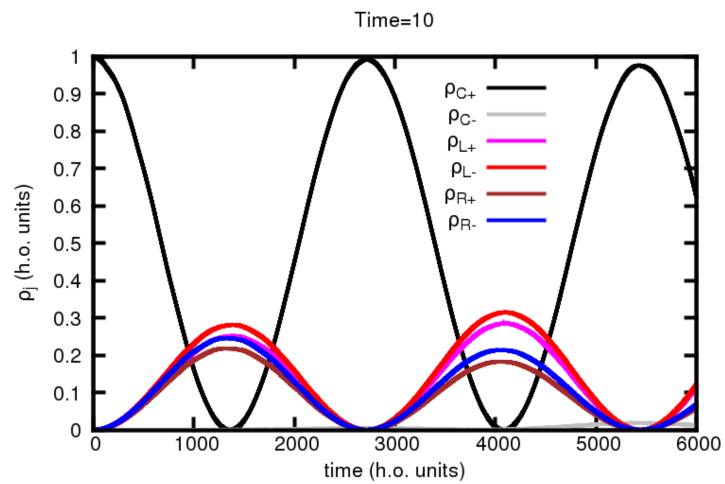
$J_3 = J_{L,n}^{C,-n}$

$$\hat{H}^{m,l} = \frac{\hbar}{2}\begin{pmatrix} 0 & J_1 & J_2 & J_3 & 0 & 0 \\ J_1 & 0 & J_3 & J_2 & 0 & 0 \\ J_2 & J_3 & 0 & 0 & J_2 & |J_3|e^{-in\pi} \\ J_3 & J_2 & 0 & 0 & |J_3|e^{in\pi} & J_2 \\ 0 & 0 & J_2 & J_3 e^{-in\pi} & 0 & J_1 e^{-in\pi} \\ 0 & 0 & J_3 e^{in\pi} & J_2 & J_1 e^{in\pi} & 0 \end{pmatrix}$$

Triangular configuration







r_0=5
d=14.5 and $|J_{j,1}^{C,1}| = 3.06 \times 10^{-3}$ $|J_{j,1}^{C,-1}| = 3.28 \times 10^{-3}$

$|J_{j,1}^{j,-1}| = 4.06 \times 10^{-4}$ in h.o. units

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Triangular configuration

Assumptions → L-R decoupled

Assumptions → $J^{L-}_{L+} = J^{R-}_{R+} = 0$

$\Theta = \pi/2$

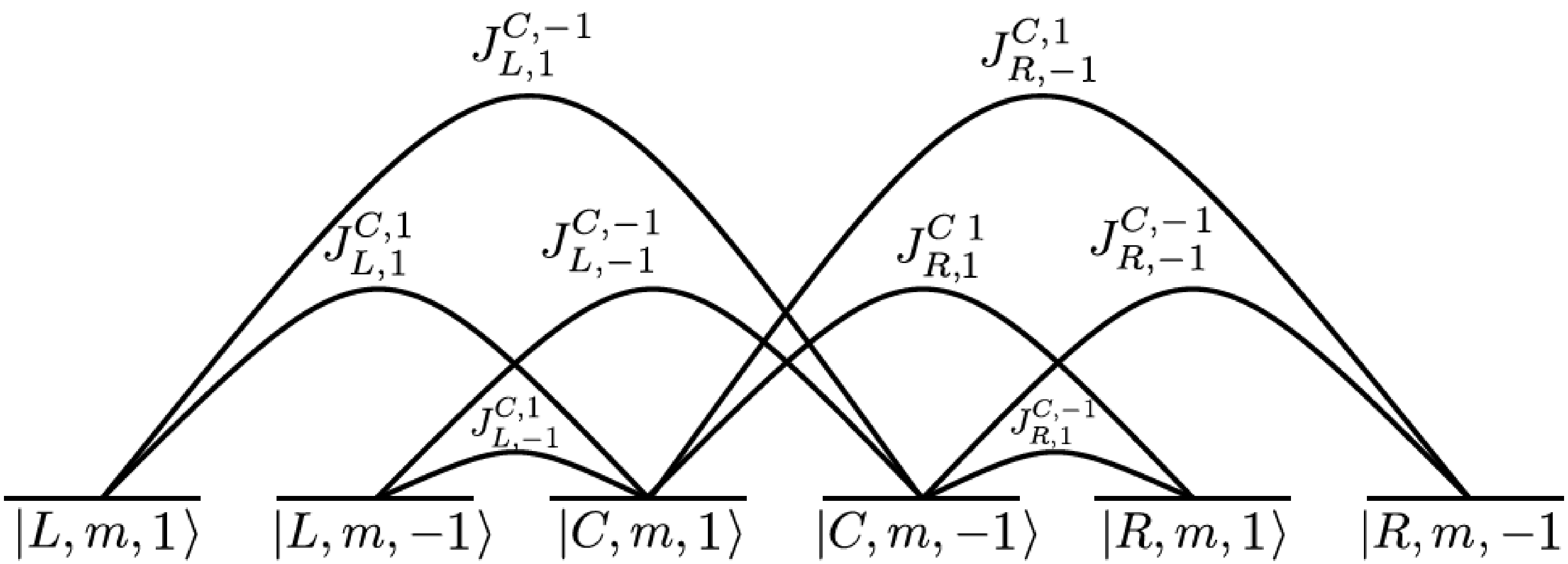
$l = 1$

⇒

$J^{C,-1}_{C,+1} = 0$

$J^{C,1}_{L,+1} \in \mathbb{R}$

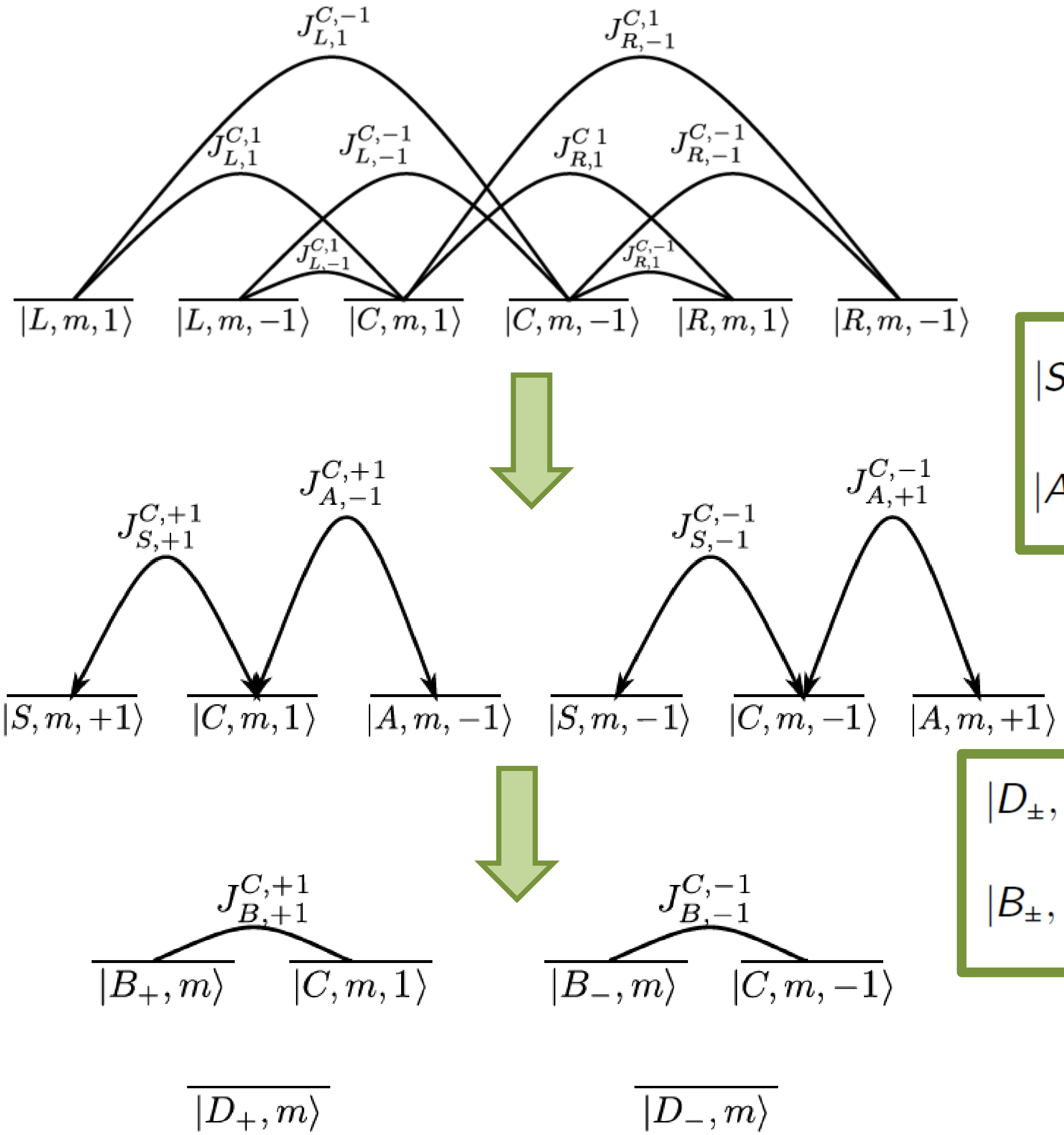
$J^{R,-1}_{C,+1} = |J^{L,-1}_{C,+1}| e^{i\pi}$



Triangular configuration

$\Theta = \pi/2$

$l = 1$



$$|S,m,\pm1\rangle = \frac{1}{\sqrt{2}}\left(|L,m,\pm1\rangle + |R,m,\pm1\rangle\right)$$

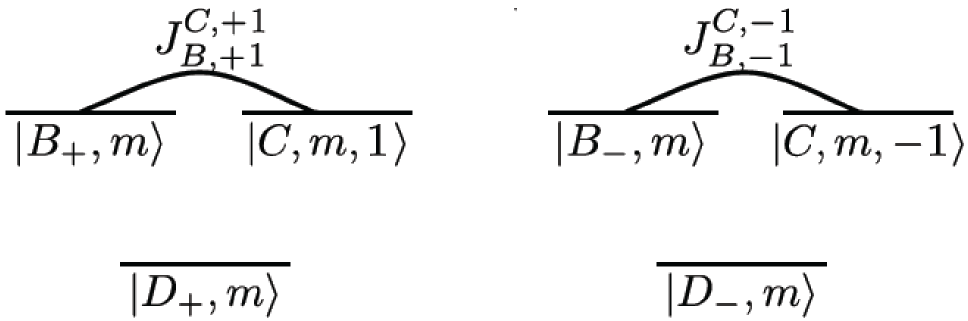
$$|A,m,\pm1\rangle = \frac{1}{\sqrt{2}}\left(|L,m,\pm1\rangle - |R,m,\pm1\rangle\right)$$

$$|D_\pm,m\rangle \equiv \frac{1}{J}\left(J_{L,n}^{C,-n}|S,m,\pm1\rangle - J_{L,n}^{C,n}|A,m,\mp1\rangle\right)$$

$$|B_\pm,m\rangle \equiv \frac{1}{J}\left(J_{L,n}^{C,n}|S,m,\pm1\rangle + J_{L,n}^{C,-n}|A,m,\mp1\rangle\right)$$

where $J = \sqrt{(J_{L,n}^{C,-n})^2 + (J_{L,n}^{C,n})^2}$

Triangular configuration

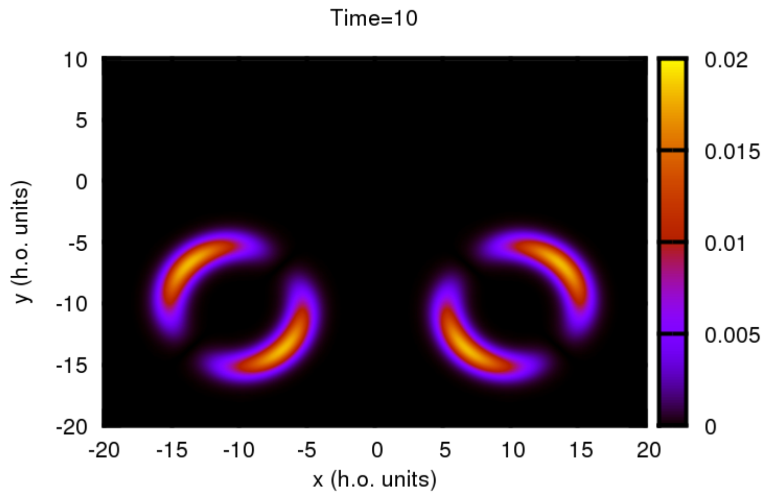


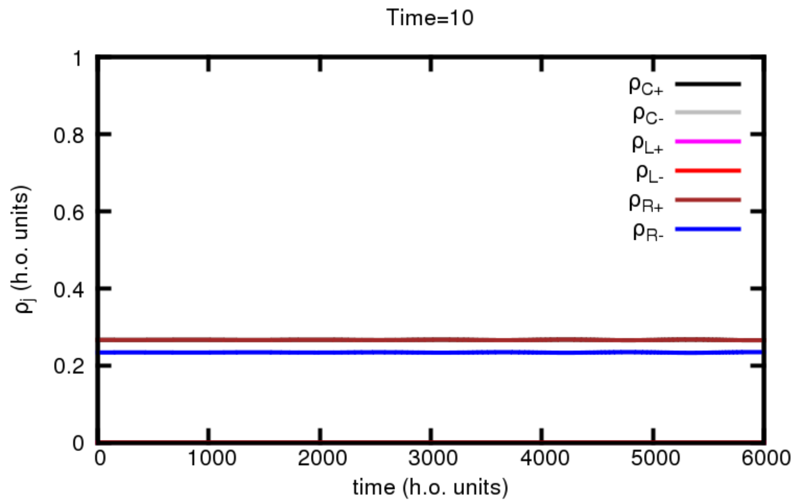
$$|D_+,m\rangle \equiv \frac{1}{J}\left(J_{L,n}^{C,-n}|S,m,+1\rangle - J_{L,n}^{C,n}|A,m,-1\rangle\right)$$

where

$$|S,m,+1\rangle = \frac{1}{\sqrt{2}}\left(|L,m,+1\rangle + |R,m,+1\rangle\right)$$

$$|A,m,-1\rangle = \frac{1}{\sqrt{2}}\left(|L,m,-1\rangle - |R,m,-1\rangle\right)$$





Triangular configuration

What happens for $\Theta \neq \pi/2$ or for $|n| \neq 1$?

For an arbitrary angle we see that:

$$J^{C,\pm n}_{D,\pm n} = \frac{J_2 J_3}{\sqrt{2}\sqrt{J_2^2 + J_3^2}}\left(1 + e^{\pm 2in\Theta}\right)$$

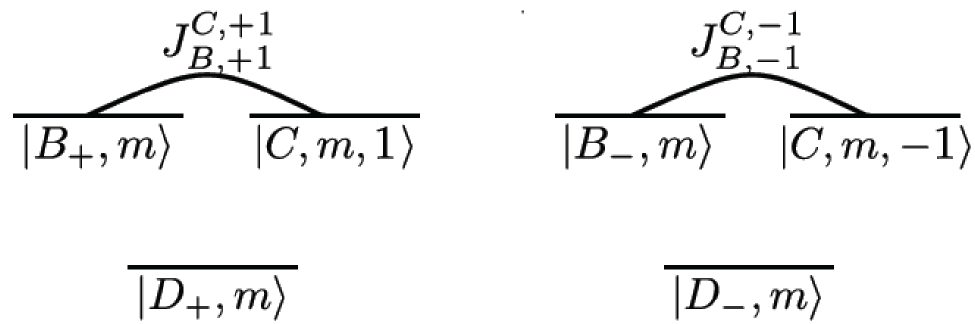
$$J^{C,\mp n}_{D,\pm n} = \frac{J_3^2}{\sqrt{2}\sqrt{J_2^2 + J_3^2}}\left(1 + e^{\pm 2in\Theta}\right)$$

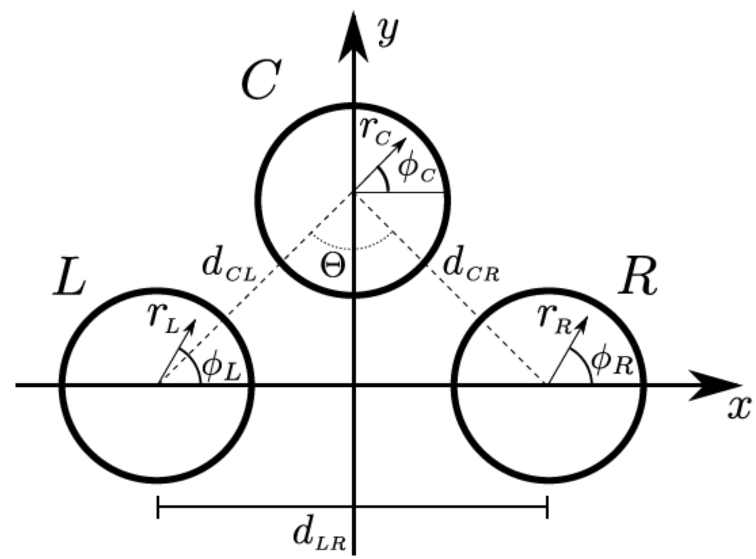
$$\boxed{\Theta = \frac{\pi}{2}\left(\frac{2k+1}{n}\right) \quad \text{with } k \in \mathbb{N}}$$

where $J_1 = J^{L,-n}_{L,n}$

$J_2 = J^{C,n}_{L,n}$

$J_3 = J^{C,-n}_{L,n}$





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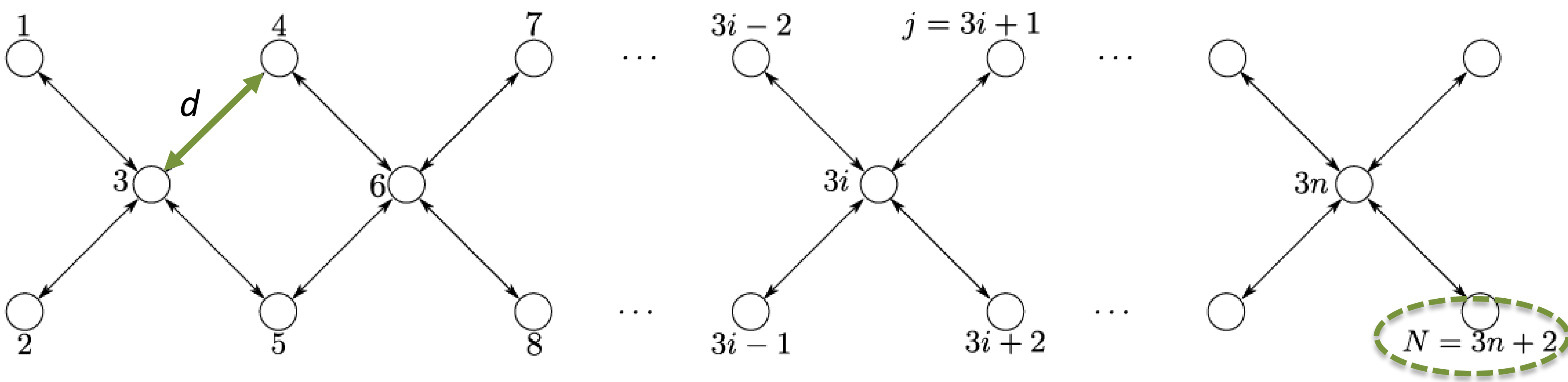
Edge-like states in an optical ribbon

Edge-like states → **robust due to quantum interference effects**

Ribbon of n cells



Manifolds of N(l+1) degenerated states →

$$\hat{H}_{\text{ribbon}} = \sum_{l=0}^{\infty} \hat{H}_l$$

→ *l = 0*

→ *l =1*

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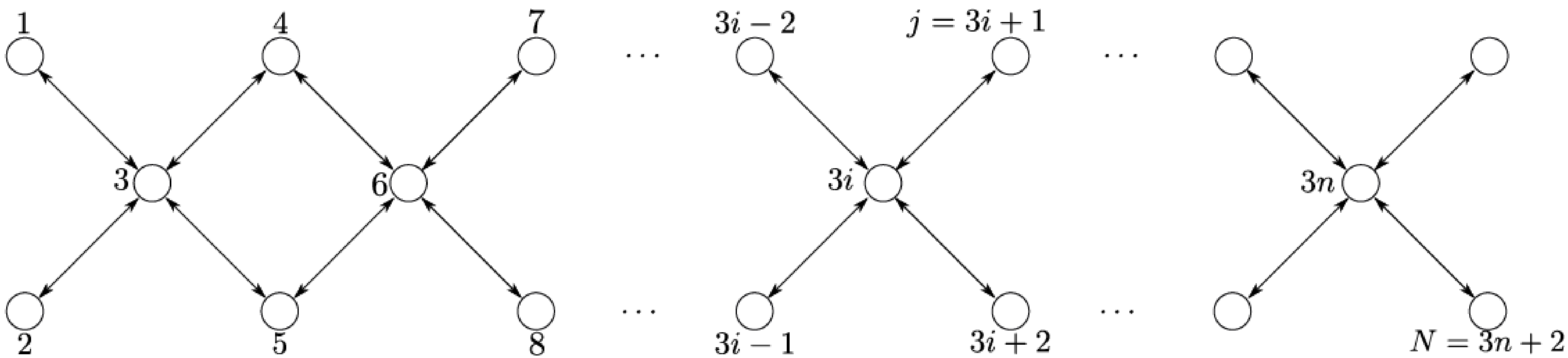
Edge-like states in an optical ribbon

Manifold of ground states, *l = 0* $\{|j\rangle\}$ $j = 1, \dots, N$

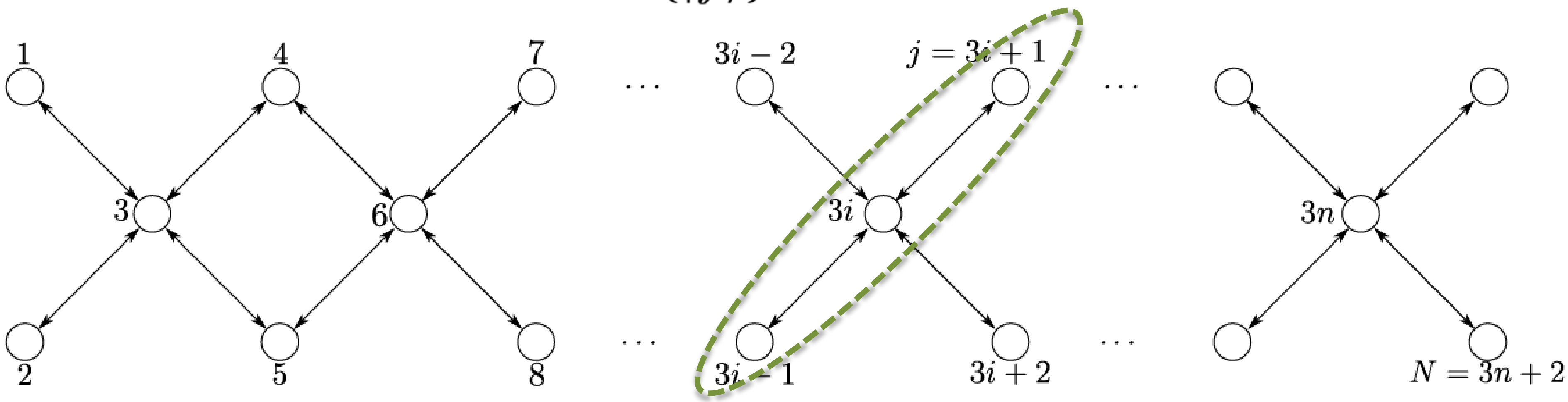


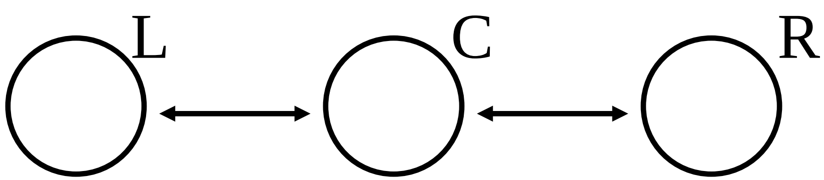
$$\hat{H}_0 = -\hbar J \sum_{i=1}^{n} \left[\left(\hat{a}^\dagger_{3i-2} \hat{a}_{3i} + \hat{a}^\dagger_{3i-1} \hat{a}_{3i} + \hat{a}^\dagger_{3i+1} \hat{a}_{3i} + \hat{a}^\dagger_{3i+2} \hat{a}_{3i} \right) + h.c. \right]$$

$$\hat{a}^\dagger_k \hat{a}_j \, |h\rangle = |k\rangle \, \delta_{jh}$$

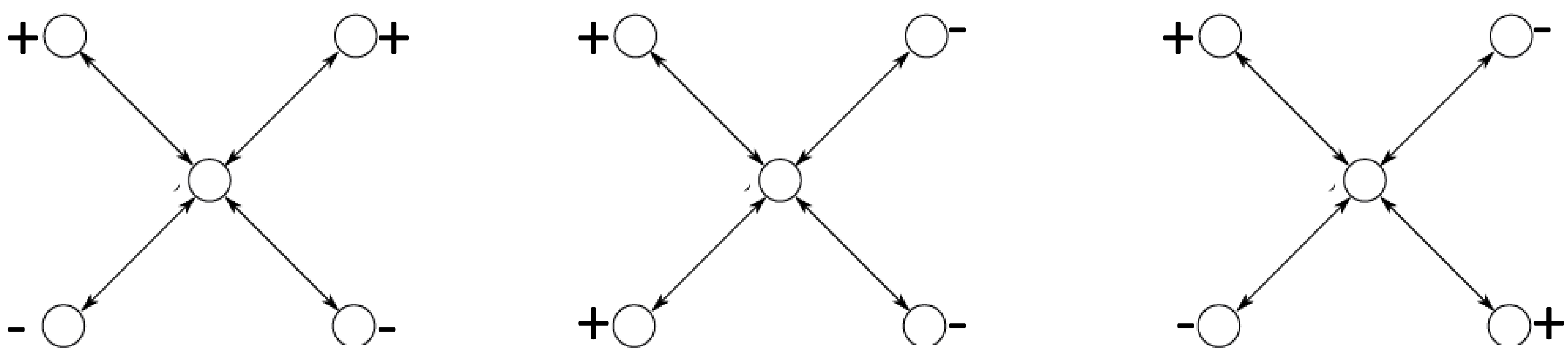
Edge-like states in an optical ribbon

Manifold of ground states, *l = 0* $\{|j\rangle\}$ $j = 1, \dots, N$





$$|D\rangle = \frac{1}{\sqrt{2}}(|L\rangle + e^{i\pi}\,|R\rangle)$$



Edge-like states in an optical ribbon

Manifold of ground states, *l = 0*

For a ribbon of n cells → 2^n+1 possible edge-like states ⇕ eigenstates of H_0

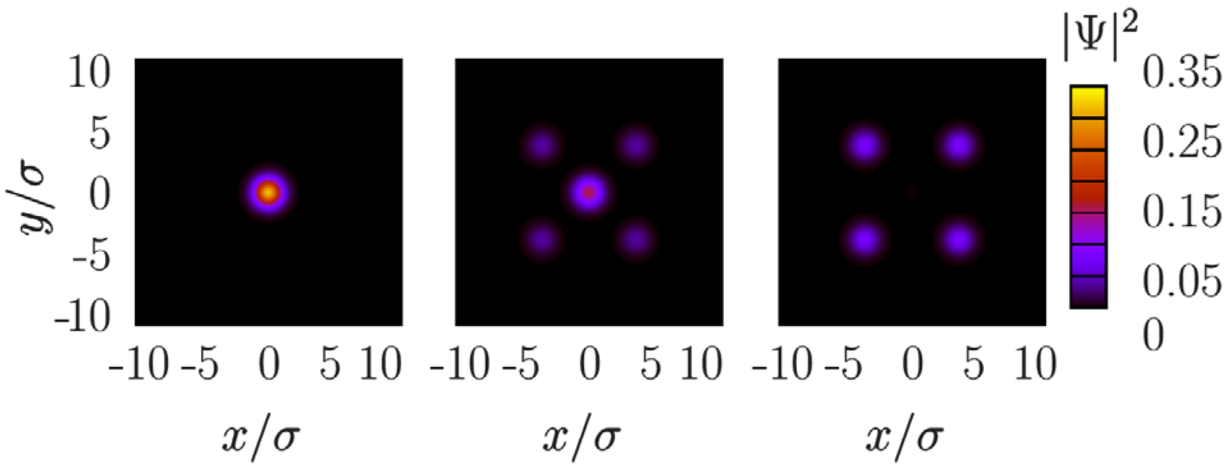
$$|D_k\rangle_{l=0} = \frac{1}{\sqrt{2(n+1)}}\left(|1\rangle + e^{i\pi}|2\rangle + \sum_{j=1}^{n}(-1)^{B_k^j(n)}\left(|3j+1\rangle + e^{i\pi}|3j+2\rangle\right)\right)$$

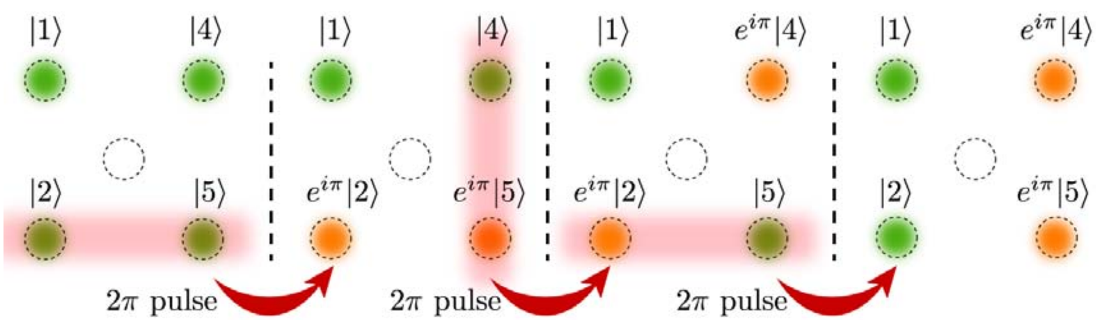
$$|D_{2^n}\rangle_{l=0} = \frac{1}{\sqrt{2(n+1)}}\sum_{j=0}^{n} e^{j\cdot i\pi}\left(|3j+1\rangle + |3j+2\rangle\right)$$

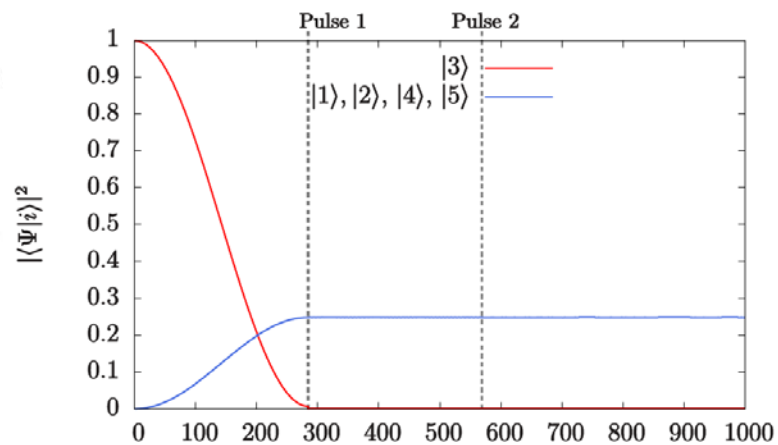
where $k = 0, \ldots, 2^n - 1$ and $B_k^j(n)$ is the jth digit (starting from the left) of the binary representation of k using a total of n digits, i.e., $B_7(n=4) = 0111$, $B_7^1(n=4) = 0$ and $B_7^2(n=4) = 1$.

Edge-like states in an optical ribbon

Manifold of ground states, *l = 0*



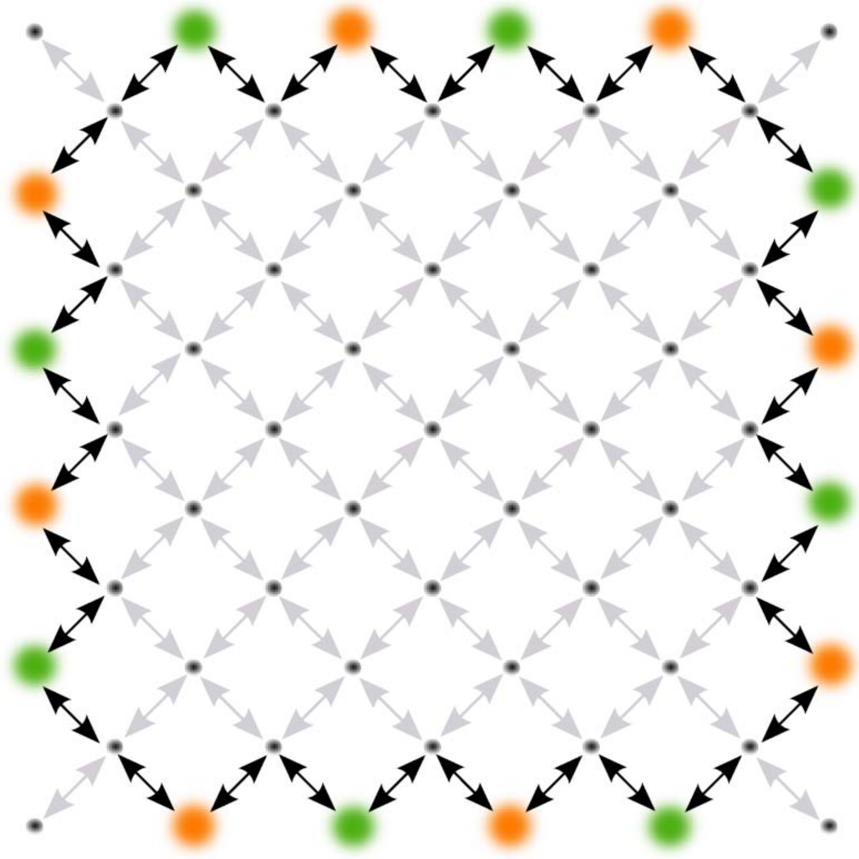




Edge-like states in an optical ribbon

Manifold of ground states, *l = 0*

Generalization to other geometries



Outline

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  - Introduction
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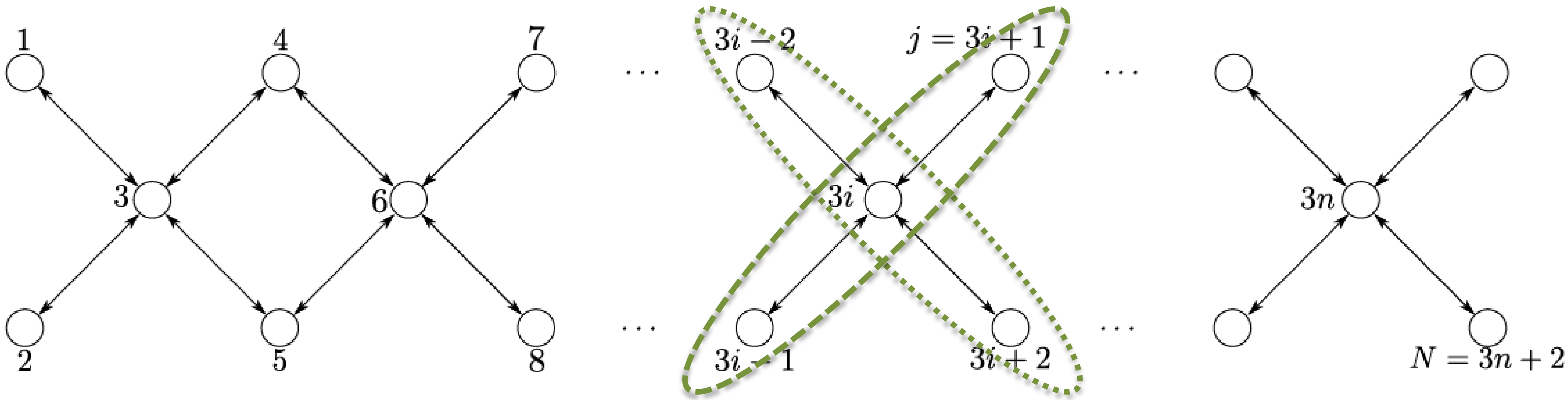
Edge-like states in an optical ribbon

Manifold of OAM states *l* = 1 $\{|j,+\rangle\,,|j,-\rangle\}\qquad j=1,\ldots,N$

$$\langle\vec{r}|j,\pm\rangle\sim\Psi(r_j)e^{\pm i(\phi_j-\phi_0)}$$



Self-coupling

$$J_1\sim|\langle j,\pm|\hat{H}|j,\mp\rangle|$$

Cross-couplings

$$J_2\sim|\langle j,\pm|\hat{H}|k,\pm\rangle|$$
$$J_3\sim|\langle j,\pm|\hat{H}|k,\mp\rangle|$$

ϕ_0=-π/4

$3i-2\leftrightarrow 3i$
$3i\leftrightarrow 3i+2$

Real

$3i-1\leftrightarrow 3i$
$3i\leftrightarrow 3i+1$

π phase

Edge-like states in an optical ribbon

Manifold of OAM states *l* = *1*

$$\hat{a}^\dagger_{j,\alpha''}\hat{a}_{k,\alpha'}\,|h,\alpha\rangle = |j,\alpha''\rangle\,\delta_{kh}\delta_{\alpha'\alpha}$$

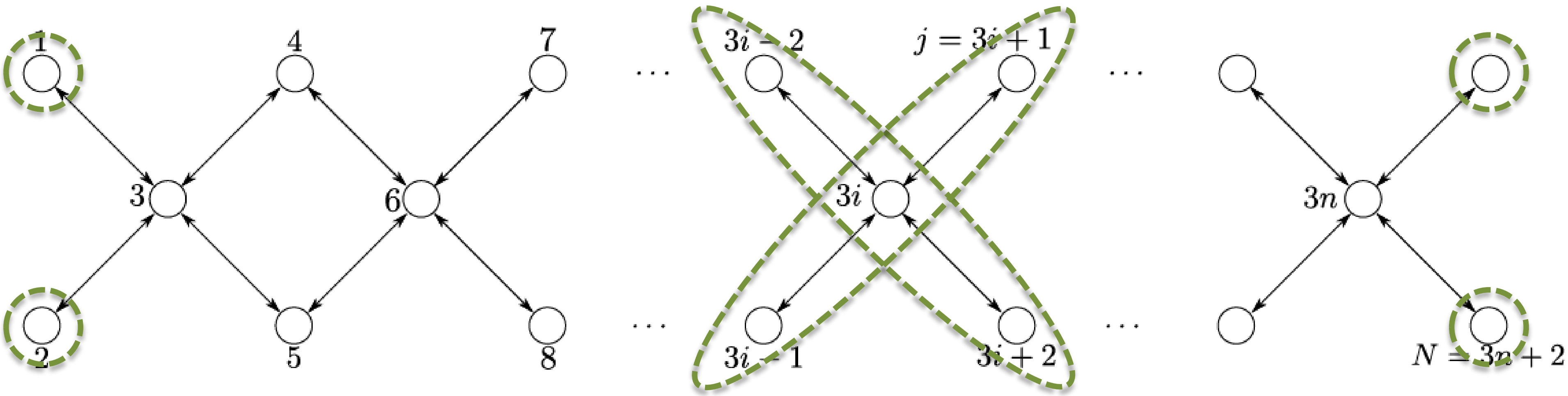
$$\begin{aligned}\hat{H}_1 = &-\hbar\sum_{i=1}^{n}\sum_{\alpha,\alpha'=\pm1}(U_1)_{\alpha\alpha'}(\hat{a}^\dagger_{3i,\alpha}\hat{a}_{3i-1,\alpha'} + \hat{a}^\dagger_{3i,\alpha}\hat{a}_{3i+1,\alpha'})\\ &-\hbar\sum_{i=1}^{n}\sum_{\alpha,\alpha'=\pm1}(U_2)_{\alpha\alpha'}(\hat{a}^\dagger_{3i,\alpha}\hat{a}_{3i-2,\alpha'} + \hat{a}^\dagger_{3i,\alpha}\hat{a}_{3i+2,\alpha'})\\ &-\hbar\sum_{\alpha,\alpha'}(S_1)_{\alpha\alpha'}(\hat{a}^\dagger_{1,\alpha}\hat{a}_{1,\alpha'} + \hat{a}^\dagger_{N-1,\alpha}\hat{a}_{N-1,\alpha'})\\ &-\hbar\sum_{\alpha,\alpha'}(S_2)_{\alpha\alpha'}(\hat{a}^\dagger_{2,\alpha}\hat{a}_{2,\alpha'} + \hat{a}^\dagger_{N,\alpha}\hat{a}_{N,\alpha'}) + \text{H.c.},\end{aligned}$$

$$U_1 = \begin{pmatrix} J_2 & J_3 e^{-i\pi} \\ J_3 e^{i\pi} & J_2 \end{pmatrix} \qquad S_1 = \begin{pmatrix} 0 & J_1 \\ J_1 & 0 \end{pmatrix}$$

$$U_2 = \begin{pmatrix} J_2 & J_3 \\ J_3 & J_2 \end{pmatrix} \qquad S_2 = \begin{pmatrix} 0 & J_1 e^{-i\pi} \\ J_1 e^{i\pi} & 0 \end{pmatrix}$$

Edge-like states in an optical ribbon

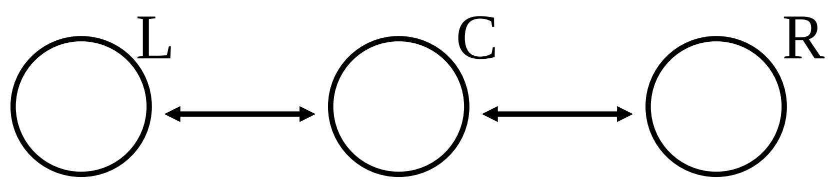
Manifold of OAM states *l = 1* $\phi_0 = -\pi/4$



J_1 only at the corners

$|J_1| \ll |J_2|, |J_3|$

$|J_2| \approx |J_3|$



$$|D+\rangle = \frac{1}{2}(|L,+\rangle + |L,-\rangle - |R,+\rangle - |R,-\rangle)$$

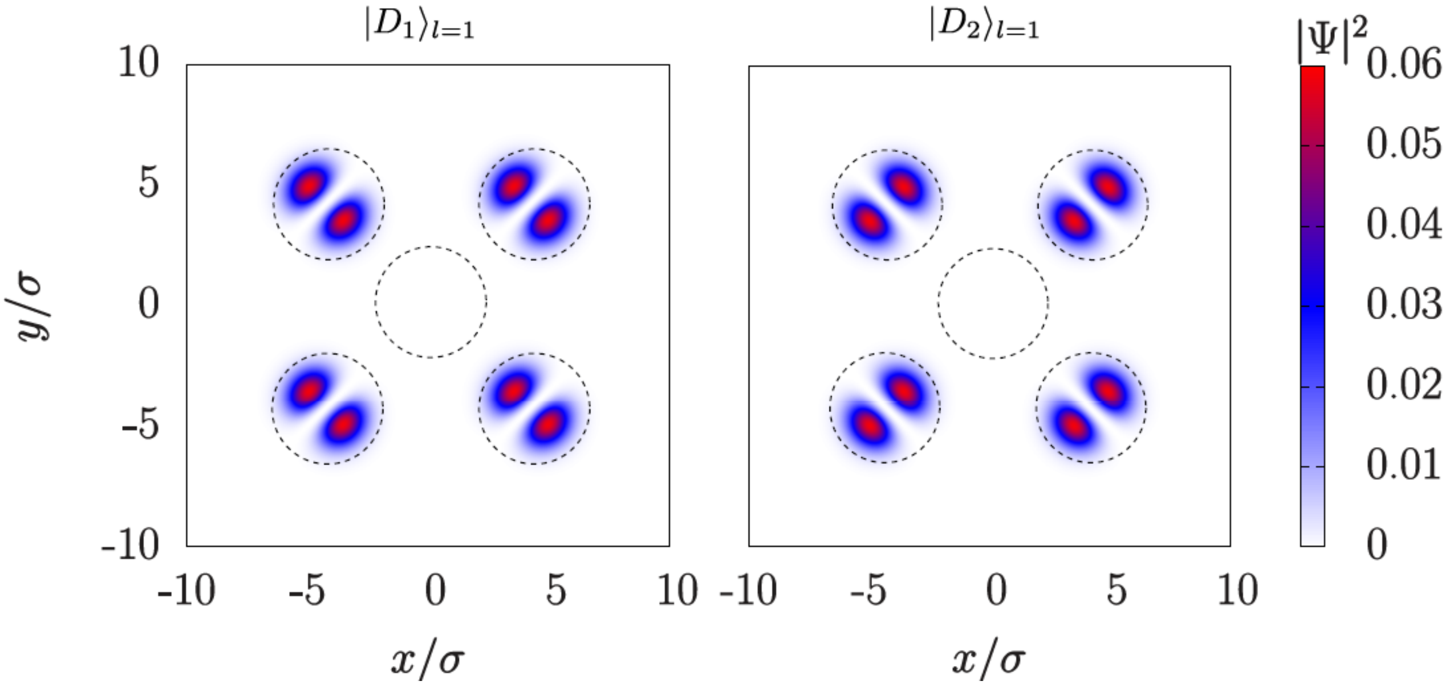
$$|D-\rangle = \frac{1}{2}(|L,+\rangle - |L,-\rangle - |R,+\rangle + |R,-\rangle)$$

Edge-like states in an optical ribbon

Manifold of OAM states *l = 1* $\phi_0=-\pi/4$

$$|D_1\rangle_{l=1} = \frac{1}{\sqrt{4(n+1)}}\sum_{j=0}^{n}\left(\left(|3j+1,+\rangle + |3j+1,-\rangle\right) + e^{i\pi}\left(|3j+2,+\rangle + |3j+2,-\rangle\right)\right)$$

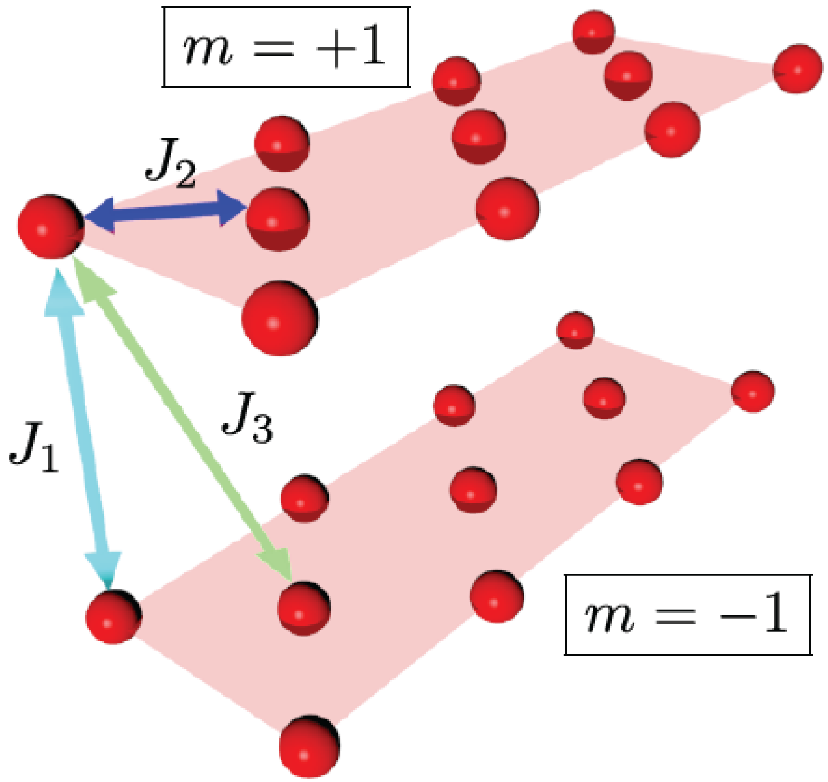
$$|D_2\rangle_{l=1} = \frac{1}{\sqrt{4(n+1)}}\sum_{j=0}^{n}\left(\left(|3j+1,+\rangle - |3j+1,-\rangle\right) + e^{i\pi}\left(|3j+2,+\rangle - |3j+2,-\rangle\right)\right)$$



Edge-like states in an optical ribbon

Manifold of OAM states *l = 1*

Winding number associated to the orbital angular momentum as synthetic dimension



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Edge-like states in an optical ribbon

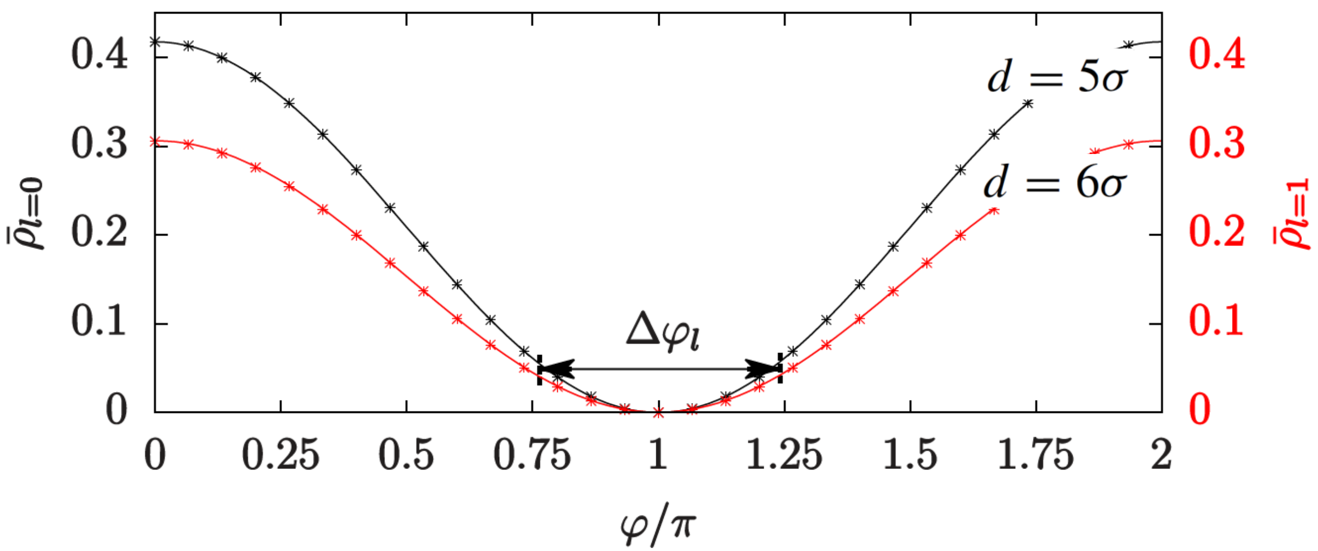
Robustness

⇨ **against phase differences**

Trial states in a ribbon of 2 cells:

***l* = 0** $$|\Psi(\varphi)\rangle_{l=0} = \frac{1}{\sqrt{6}} \sum_{j=0}^{2} \left(|3j+1\rangle + e^{i\varphi} |3j+2\rangle \right)$$

***l* = 1** $$|\Psi(\varphi)\rangle_{l=1} = \frac{1}{\sqrt{12}} \sum_{j=0}^{2} \left((|3j+1,+\rangle + |3j+1,-\rangle) + e^{i\varphi} (|3j+2,+\rangle + |3j+2,-\rangle) \right)$$



$$\bar{\rho}_l(\varphi) = \sum_{i=1,2} \frac{1}{T} \int_0^T dt \left| \left\langle 3i \left| e^{-i\hat{H}t/\hbar} \right| \Psi(\varphi) \right\rangle_l \right|^2$$

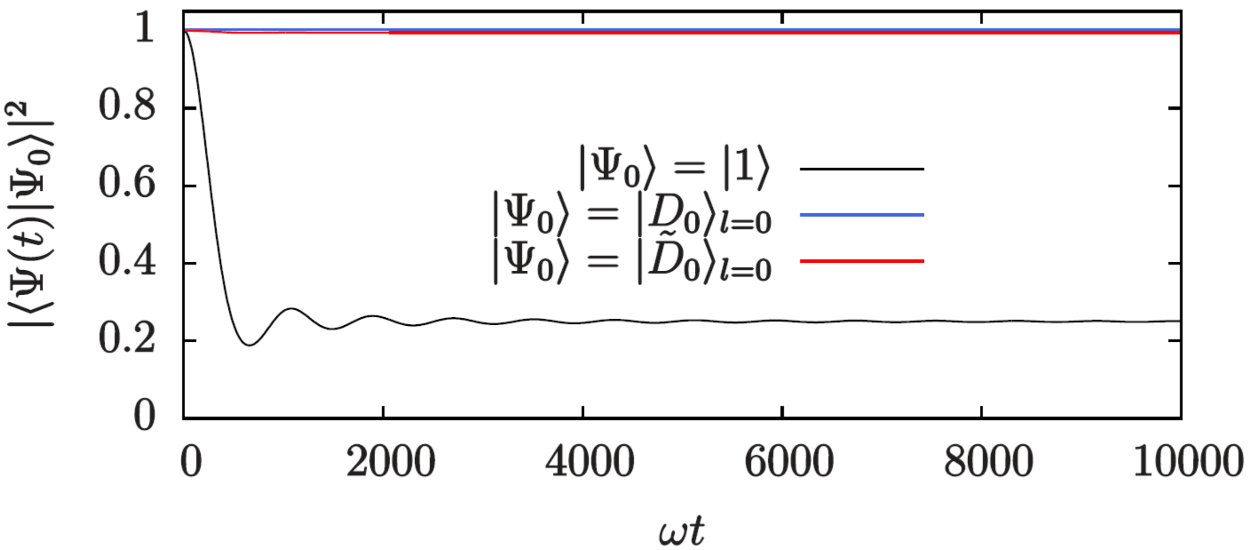
average value of the population of the central sites

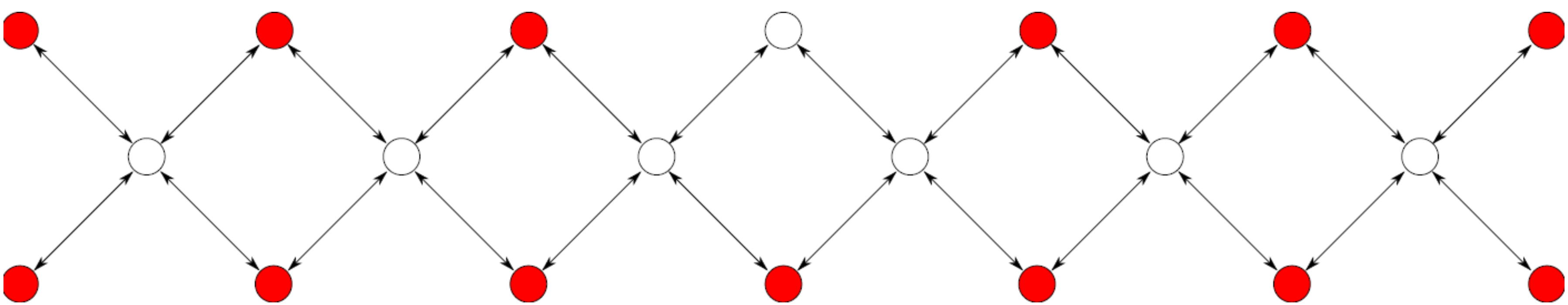
Edge-like states in an optical ribbon

Robustness

➡ **against local perturbations**

ribbon of 100 cells

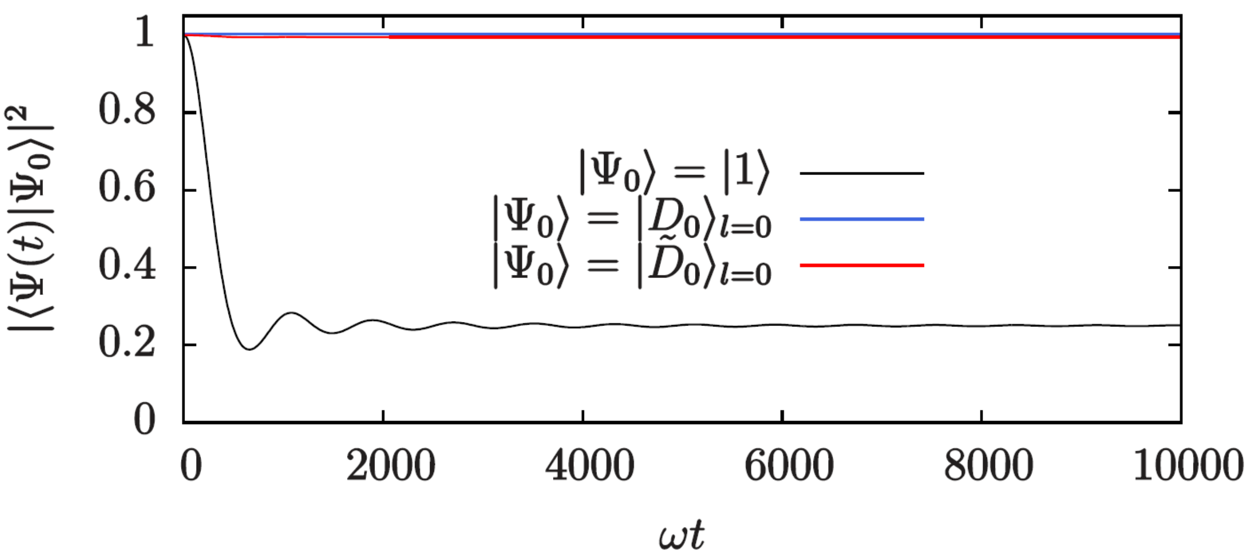


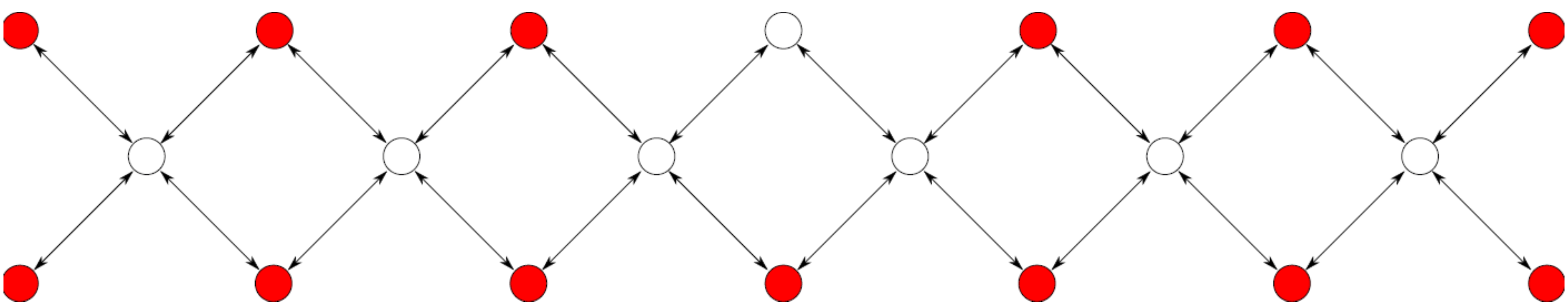


Edge-like states in an optical ribbon

Robustness

⟹ **against local perturbations** ribbon of 100 cells

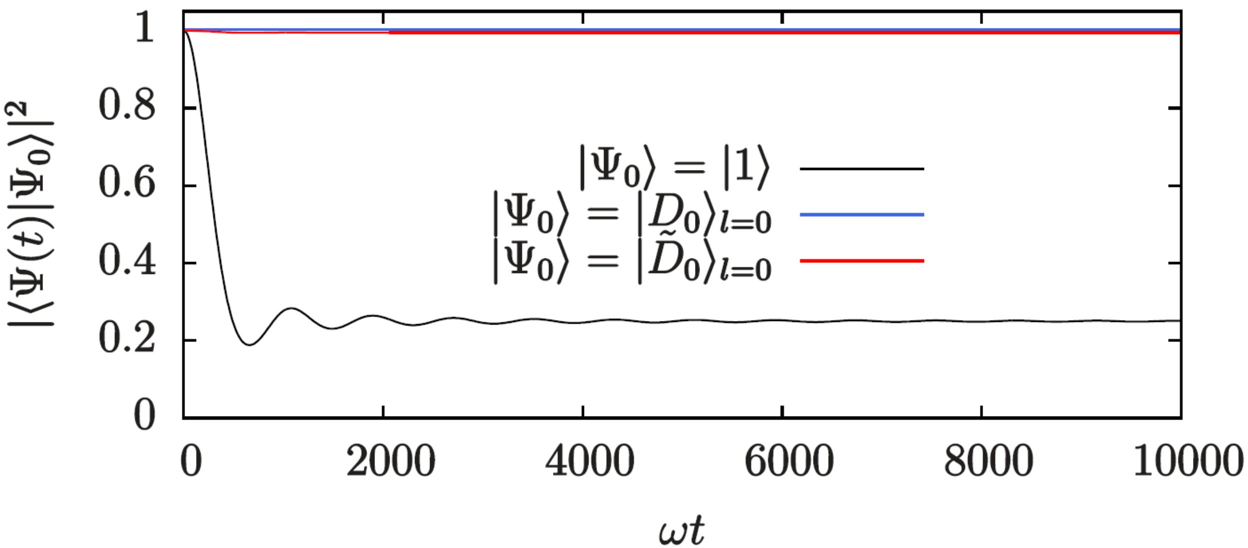


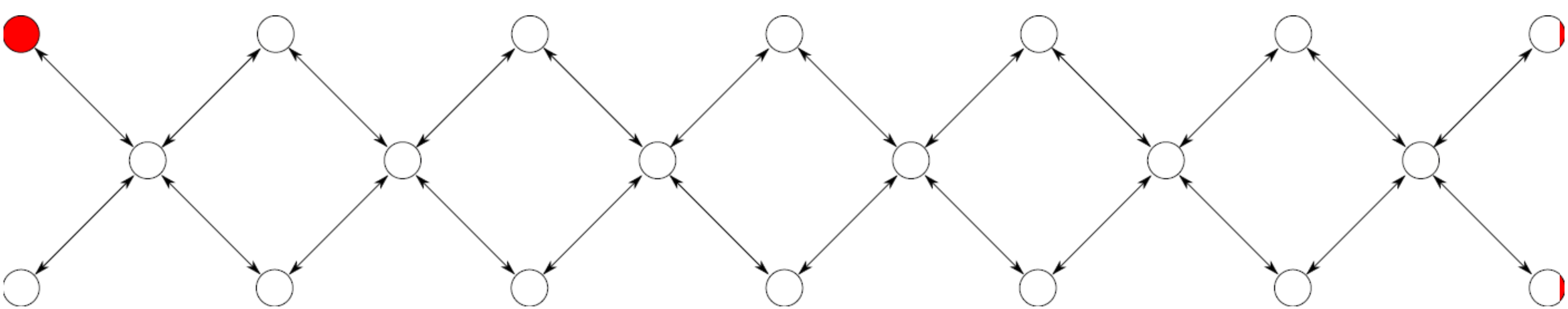


Edge-like states in an optical ribbon

Robustness

⇨ **against local perturbations** ribbon of 100 cells





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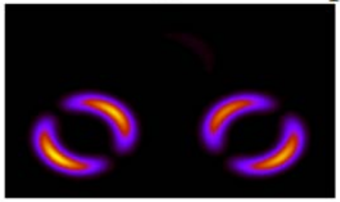
Conclusions

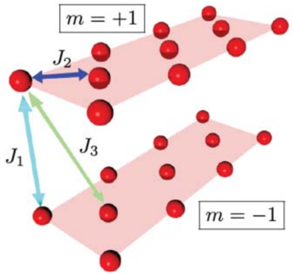
Geometrically induced complex tunneling



- By means of geometrical symmetries it is shown that angular momentum states in sided-coupled cylindrically symmetric potentials exhibit complex tunneling amplitudes.
- In a system of three rings the complex nature of the tunneling plays crucial role in the dynamics.
- In a triangular ring configuration, complex tunneling amplitudes allow engineering spatial dark states via quantum interference.

Conclusions

Edge-like states in an optical ribbon



- ELS using states with l = 0 and l = 1 in a ribbon based on spatial dark states are predicted.

- The experimental implementation of these ELS for l = 0 and the switch from one ELS to another using laser pulses is discussed.

- The robustness of these states under relative phase variations and when including a defect on the lattice is demonstrated.

- The winding number can be regarded as a synthetic dimension.

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http://grupsderecerca.uab.cat/qaos/

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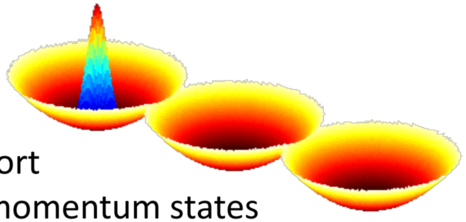
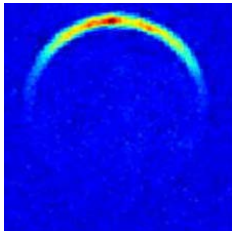


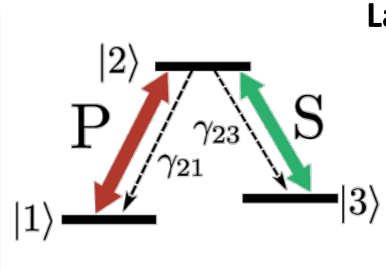
Ultracold atoms

Quantum transport
Orbital angular momentum states
Complex tunneling

Conical Refraction



Fundamentals: theory and experiment
Applications: trapping microparticles and BECs

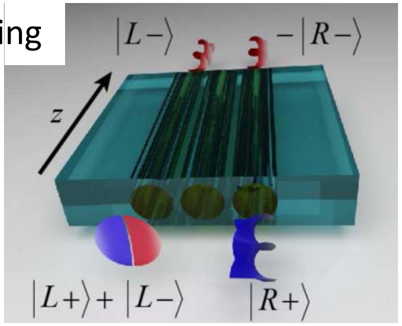


Laser-matter interaction

Nanoscopy
Atomic frequency combs
Spin-orbit coupling

Light propagation in coupled optical waveguides

Dark and bright OAM modes
SUSY techniques for mode filtering



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