

Open Quantum Many-Body Systems

Dissipative formation of quantum spin dimers

Peter Zoller

INT discussion, April 6 2015

This talk: *Chiral* Spin Networks

driven two-level atoms / spins

wave guide

Wave guide for …

- photons ✓ optical - photonic nanostructures
	- ✓ microwave superconducting circuits
- phonons ✓ spin-orbit coupled BEC ✓ nano-mechanics
- spin-waves
- ✓ Rydberg atoms ✓ trapped ions

Dissipative formation of quantum spin dimers

Equilibrium vs. Non-Equilibrium Quantum Many-Body Physics

• thermodynamic equilibrium

What "condensed matter physicists / theorists" get excited about

Toy Models (1D) $\ddot{\hspace{1cm}}$ τ as follows. For τ physical space but rather relate to SU!3" rotations in an in- $\begin{array}{ccc} \n\text{SUS} & \text{SUS} & \text{SUS} \ \n\end{array}$

! \mathbb{L}

chains exhibit spinon confinement and a Haldane gap.

emerging rules to investigate and motivate which SU!*n*" spin

MARTIN GREITER AND STEPHAN RACHEL PHYSICAL REVIEW B **75**, 184441 !2007"

• Majumdar-Ghosh (spin-½): *parent* Hamiltonian • Majumdar-Qhosh (spin-½): *paren*t Hamiltonian model for SU 3" spin chains in Sec. II. This model consists in interactions, with a threefold degenerate ground state, in the state, in the state, in the state, in the state, may assume, subject to the requirement that the number of ndar-Gnosh (spin-*½): paren*#Hamiltonian

where the product runs over all even sites *i* for one state and over all odd sites for the other, are exact zero-energy ground states65 of the parent Hamiltonian which triples of neighboring sites form SU!3" singlets !or trimers". In Sec. IV, we review the representations of SU!3", which we use to verify the trimer model in Sec. V. In this *^H*MG ⁼# **II. MAJUMDAR-GHOSH MODEL**

$$
H_{\text{MG}} = \sum_{i} \left(S_{i} S_{i+1} + \frac{1}{2} S_{i} S_{i+2} + \frac{3}{8} \right) \quad \text{with} \quad S_{i} = \frac{1}{2} \sum_{\tau, \tau' = \uparrow, \downarrow} c_{i\tau}^{\dagger} \sigma_{\tau \tau'} c_{i\tau'}
$$

$$
\big| \psi_{\text{MG}}^{\text{even}} \, \big\rangle \; = \; \prod_{\genfrac{}{}{0pt}{}{i \text{ even}}{(i \text{ odd})}} \Big(c_{i\uparrow}^{\dagger} c_{i+1\downarrow}^{\dagger} - c_{i\downarrow}^{\dagger} c_{i+1\uparrow}^{\dagger} \Big) \, | \, 0 \, \rangle = \qquad \qquad \text{quantum dimers}
$$

$$
= \begin{cases} \mid \circ \hspace{-0.5ex} \bullet \hspace{-0.5ex} \circ \hspace{-0.5ex} \bullet \hspace{-0.5ex} \circ \hspace{-0.5ex} \bullet \hspace{-0.5ex} \circ \hspace{-0.5ex} \circ \hspace{-0.5ex} \circ \hspace{-0.5ex} \rangle & \text{``even''} \\ \mid \hspace{-0.5ex} \circ \hspace{-0.5ex} \rangle & \text{``odd''} \end{cases}
$$

 $\frac{1}{2}$ valence bond so $\overline{}$ valence bond solid

[|] ❝❝❝❝❝❝❝ ⟩ "odd"!1"

where the product runs over all even sites *i* for one state and

over all odd sites for the other, are exact zero-energy ground α are exact zero-energy ground α

1 • AKLT, Haldane Shastry, SU(N) models, ... be ¹ view of the MG model in Sec. II, we introduce the trimer where the product runs over all even sites *i* for one state and • AKLT, Haldane Shastry, SU(N) models, ...

we will sl $\frac{1}{2}$ $\mathcal{L}_{\mathcal{A}}$ Clearly State in which the total spin of the total spin of the total spin of the total spin of the total spin o SU!3" to SU!*n*". In Sec. X, we use the rules emerging from Below we will show that *pul* to invento in the models of driven-dissinative (or exhibit spinon confidence gap. In this con-² or ² , as **²** ! **¹ ²** ! **¹ 2** = **²** " **¹ ²** " **³ ²** ." In the dimer states above, pin dimers can also form as *steady state* is system / non-equilibrium) dynamics. pative (open system / non-e P_{Ω} interactions, which a threefted degenerations of the threefted degenerations and the state ground state ground $\overline{}$ which triples of $\mathbf C$ $\frac{1}{2}$ $\overline{\mathbf{V}}$ 2 $\overline{\text{S}}$ of driven-dissipative (open system / non-equilibrium) dynamics. 8 Below we will show that *pure spin dimers* can also form as *steady state*

New generation of quantum optics experiments:

Atoms [& Solid State Emitters] Coupled to Photonic Nanostructures

… challenges in theory

Driven-Dissipative Many-Body Quantum Systems

Trapping Atoms Close to Photonic Nanostructures mapping Atoms show to motonic is l, results in strong atom–photon interactions for an atom sufficiently ribolia to tarito $m₆$ a quantum optical section optical section optical section optical section optical section optical section opti isa to Photonic Nanostructures $\overline{\mathsf{u}}$ experiments experiments experiments experiments $\overline{\mathsf{u}}$ ica to Photonic Na σ to the from the the side of the side of the σ and to set the fiber v-groove position and width (which ultimately determined alignment of the fiberclean removes any resist residue prior to a potassium hydroxide (KOH) wet etch, which opens a through-hole in the Si

doi:10.1038/nature13188 || Nanophotonic quantum phase switch with a single atom T. G. Tiecke^{1,2*}, J. D. Thompson^{1*}, N. P. de Leon^{1,3}, L. R. Liu¹, V. Vuletić² & M. D. Lukin¹ controls the propagation of a subsequent probe field $\overline{}$ techniques pave the way to integrated quantum nanophotonic $\sum_{i=1}^n$ single atom $f(x) = \frac{d_0(110.1038/nature13188)}{dx}$ optical tweezer and its reflection from the side of the cavity (Methods t ransient coupling \mathbb{R} for experiments exploiting long atomic coherence times, and enables scaling to quantum circuits with multiple atoms. the interaction between individual photons and atoms in $\mathbf d$ do it. $\mathbf d$ D H A V PBS1 PBS2 $\frac{1}{2}$ ingle $\frac{1}{2}$ ^{2*}, J. D. Thompson¹*, N. P. de Leon^{1,3}, L. R. Liu¹, V. Vuletić² & M. D. Lukin¹ \mathcal{A}_max and \mathcal{A}_max and \mathcal{A}_max and \mathcal{A}_max and \mathcal{A}_max strate at either end of the waveguide (labeled sections B, C, ends of the multiplant multiplant multiplane and multiplane and multiplane and multiplane arrays to 15 tethers spaced at a 220 nm pitch. Finite-difference time- \mathcal{F} show that the input coupling efficiency that the input coupling efficiency of \mathcal{F} $\frac{1}{\sqrt{2}}$ After additional Nanostrip cleaning, the chip is transferred to an isopropyl alcohol solution where it is dried using a critical point drying step to prevent stiction of the double-wire \mathbf{z} $\mathbf v$ it is a surface. Once fabricated, anti-reflection coated optical fibers are mounted into the input and output v-grooves in the Si substrate. The fiber-waveguide separation is set for optimal coupling (typically !10 lm) before the fibers are affixed in place with UV curing epoxy. The Si chip and fibers are then at the attached to a vacuum-compatible model \mathcal{S}

extend the entire waveguide length and connect to the sub-

APPLIED PHYSICS LETTERS 104, 111103 (2014) $APPLIED PHI SICS LELI LERS IVA, 111103 (2014)$ $\Omega(0.14)$ CrossMark ϵ dick for updates

By analogy to transistors in classical electronic circuits, quantum \blacksquare Nanowire photonic crystal way $\frac{1}{2}$ $\frac{1}{2}$. Operation is the fundamental limit where at the fundamental limits where at the fundamental limits where at **Thomas J. Watson, Sr., Laboratory of Applied Physics 128-95, California Institute of Technology, Pasadena, Pasa** is board to a small spatial to a small spatial $\mathbf s$ an atom, is a property and charge the charge to overcoming the charge of α hotonic crystal wayequides for single-a guides for single-atom trappin PBS1 PBS2 e Nanowire photonic crystal waveguides for single-atom trapping and strong anowne prioro The nanowire waveguides as shown in Fig. 3 are formed ystai waveguiues ioi singit grown via low-pressure chemical vapor deposition on a (100) Si substrate of 200 lm thickness. This sort of SiN has transmission of the APCW, we utilize a broadband superalum trapping and strung

, such a switch may enable applications such as long-distances such as long-distances such as long- $\mathsf{S.-P. \; Yu, \mathsf{A}}$, J. D. Hood, A . A. Mun **cessing and metrology and metropology** and the Seán M. Meenehan,^{2,3} Justin D. Coher $\frac{1}{2}$ $\frac{3}{2}$ M. J. Martin, $\frac{3}{2}$ Hichard Norte, $\frac{3}{2}$ C.-L. Hung, $\frac{3}{2}$ 3 Oskar Painter, $^{2,3, b)}$ and H. J. Kimble $^{1,2, c)}$ S.-P. Yu,^{1,2,a)} J. D. Hood,^{1,2,a)} J. A. Muniz,^{1,2} M. J. Martin,^{1,2} Richard Norte,^{2,3} C.-L. Hung,^{1,2} 5.1
Ne Seán M. Meenehan, 2,3 Justin D. Cohen, 2,3 Oskar Painter, $^{2,3, b)}$ and H. J. Kimble $^{1,2, c)}$ $C \cap Y_1, 1, 2, a)$ US Sean M. Meenehan, ^{2,8} Justin D. Cohen, ^{2,8} Oskar Painter, ^{2,8,9} and H. J. Kimble 19,99 exhibited low optical loss in the near-infrared33–35 and large $t^{1,2, a}$, J. A. Muniz, $t^{1,2}$ M. J. Martin, $t^{1,2}$ Richa istin D. Cohen 2,3 Oskar Painter $^{2,3, \mathsf{b)}}$ an $t_{\text{max}} = t_{\text{max}}$, with the nanowire waveguides extend- $\overline{3}$ Norte, \sim C.-L. Hung, \sim desired photonic band $\mathsf{R}^{1,2,\mathsf{C}}$ edges closely aligned with the D1 and D1

 \blacksquare We present a comprehensive study of dispersion-engineered nanowire Γ realize a system in which a system in which a single atom switches the phase of atom switches the phase of atom system in Γ p_{in} suitable for experiments in quantum of $\frac{1}{\sqrt{1}}$ and atomic physics with optically trapped atom ∞ and ability physics with optically trapped atom z y We present a comprehensive study of dispersion-engineered nanowire photonic crystal waveguides suitable for experiments in quantum optics and atomic physics with optically trapped atoms. iantum optics and atomic physic $\frac{1}{\sqrt{1-\frac{1$ with optically trapped atoms.

system4

light.

light.

from SEM images.

states of matter7

contarly photopic or yetal wouse quide alligator priotorile crystal wave guide polarizing beam splitter (PBS2) splitter (PBS2 All any anigator priotorile crystal wave guide micro-ring optical cavities near 800 nm.1,33 Fabrication of the waveguide chip begins with a UV little chip begins with a UV of the UV of the UV of the UV of th define the back window region. We then use a single e-beam ments for similar waveguides, we estimate that the power /stal wave quide "alligator" photonic crystal wave guide

Chiral Nanophotonic Waveguide Interface Object Newceptonic Weycanida Into **Crilial Nanophotonic viaveguide inte**

NANOPHOTONICS

Directional nanophotonic atom-waveguide interface based on spin-orbit interaction of light

R. Mitsch, C. Sayrin, B. Albrecht, P. Schneeweiss, and A. Rauschenbeutel

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A chiral spin-photon interface for scalable on-chip quantum-information processing

Immo Söllner,* Sahand Mahmoodian,* Alisa Javadi, and Peter Lodahl[†]
Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen, Denmark (Dated: June 18, 2014)

-
- **• why?**
	- quantum info / non-equilibrium cond mat (quantum phases)
- **• how? physical realization**
	- photonic & phononic (here cold gases realization) & 1D spin-wave guide

Equilibrium vs. Non-Equilibrium Quantum Many-Body Physics

• *non***-equilibrium**

Many body Quantum Optics

• Dynamics: Master equation • Steady state:

$$
\dot{\rho}(t)=-\frac{i}{\hbar}[H_{\rm sys},\rho(t)]+\mathcal{L}\rho(t)
$$

validity …

$$
\rho(t) \xrightarrow{t \to \infty} \rho_{ss} = |\Psi\rangle\langle\Psi|
$$

pure & (interesting) entangled state (dark state of dissipative dynamics)

Examples: Engineered Dissipative Atomic Systems

where when the proxime values M and M are M and M are M S. Diehl et al., Nature Phys. 2012; PRL 2013 S. Diehl et al., PRL 2010 *J.* Budich et al., preprint ... Majorana edge modes

PISS. QUANTUM PNASE TRANSITIONS

d-wave pairing

Entangled States from Dissipation

 Δ Exp. neutral atoms: DeMarco, Oberthaler, ... delocalization of these pairs away from half filling. Exp. ions: Blatt et al., Nature '11; Nat Phys '13

[Polzik et al., PRL '11]

†

Topology via dissipation big-console BCS-pairing from dissipation

$\int f(x)dx$ *j>l bjl |S*i*jl |g*i *|Mq*i = *a |g*i ⌦*M^q* +X *j>l* This Talk: *Chiral* Spin Chain *bjl |S*i*jl |g*i

Theory: Master Equation for *Chiral* Spin Chains Plain-Vanilla Markovian :-)

Master equation for cascaded (purely unidirectional) quantum systems N=2: C.W. Gardiner, PRL 1993; H. Carmichael, PRL 1993; CW Gardiner & AS Parkins, PRA 1994

"Dicke" master equation for 1D: $D \text{ E } C$ hang et al 2012 New J. Phys. 14 063003

Steady states for a **chiral** waveguide

- Unique, pure steady state: $\rho(t) \xrightarrow{t \to \infty} |\Psi\rangle \langle \Psi|$.
- **Quantum Dimers**

$$
|\Psi\rangle = \bigotimes_{i=1}^{N} |D\rangle_{2i-1,2i}
$$
 singlet fraction

$$
|D\rangle = \frac{1}{\sqrt{1+|\alpha|^2}} \Big[|gg\rangle + \frac{\alpha}{\sqrt{2}} \left(|ge\rangle - |eg\rangle \right) \Big]
$$
 $\alpha = \frac{\sqrt{2}\Omega}{\delta - i(\gamma_R - \gamma_L)/2}$

• Note: only for *N* even

Understanding dark states for **N=2 spins**

Imperfections & Dark States: N=2

Physical Realizations of *Chiral* Spin Networks

Wave guide for …

- photons
- ✓ optical photonic nanostructures ✓ microwave - superconducting circuits
- phonons
- ✓ spin-orbit coupled BEC ✓ nano-mechanics

phonons

1D Chiral Spin Chains with Cold Atoms

²³ T. Ramos, H. Pichler, A.J. Daley, P.Z., PRL Dec 3 2014

- **• BEC as a "phonon reservoir"**
	- quantum reservoir engineering

• master equation

- reduced system dynamics
- Quantum Markov process

inelastic scattering from BEC as "spontaneous emission"

A Griessner, AJ Daley, SR Clark, D Jaksch, and PZ, PRL 2006 & NJPhys 2007 S Diehl, A Micheli, A Kantian, B Kraus, HP Buechler, and PZ, NatPhys 2008

- **• BEC as a "phonon reservoir"**
	- quantum reservoir engineering

• Atoms in a 1D optical lattice

- **• BEC as a "phonon reservoir"**
	- quantum reservoir engineering

• Atoms in a 1D optical lattice

• Dynamics analogous to ...

- **• BEC as a "phonon reservoir"**
	- quantum reservoir engineering

• N Atoms in a 1D optical lattice

• Dynamics analogous to ...

 Q .: How to get a E_{in} chiral reservoir?

Two-species mixture of cold quantum gases

Spin-Chain:

atoms in 1D optical lattice

AJ Daley et al., PRA **69**, 022306 (2004); A Griessner et al., PRL **97**, 220403 (2006). 28

Two-species mixture of cold quantum gases

Spin-Chain:

atoms in 1D optical lattice

AJ Daley et al., PRA **69**, 022306 (2004); A Griessner et al., PRL **97**, 220403 (2006).

Two-species mixture of cold quantum gases

Spin-Chain:

atoms in 1D optical lattice

Quantum Reservoir:

1D quasi-BEC

 $\gamma_L = \gamma_R$

Dicke superradiance & phase transition

Chiral Reservoir = Spin-Orbit Coupled BEC

Two species mixtures of cold atoms

thanks to the collaborators

Tomas Ramos

Hannes Pichler

Benoit Vermersch

Philipp Hauke

Hugo Tercas **Andrew Daley**