Crystallization of strongly interacting photons in a nonlinear optical fiber

Darrick Chang

V. Gritsev, G. Morigi, V. Vuletic, M. Lukin, E. Demler

January 9, 2008
Workshop on Quantum Noise in Correlated Systems
Motivation

Importance of quantum mechanics in emerging fields and applications

Control over light-matter interactions

Lasers

Imaging

Communication & signal processing

Spectroscopy

Ultrafast science

Optomechanical cooling

Single atoms and single photons

- Importance of quantum mechanics in emerging fields and applications

Cavity QED

Cavity-free approaches?

- Use tightly confined photons in one-dimensional waveguides

- Weak photon-atom interaction is enhanced by large # of bounces inside cavity
Photonics and QED in one dimension

- One-dimensional system: photons are constrained to move along one direction

System described by single parameter $E(z)$

- Novel physics when transverse size becomes comparable to optical wavelength, $A \sim \lambda^2$

![Diagram showing scattering probability $P \sim \frac{\sigma}{A} \sim \frac{\lambda^2}{A}$]

- Tight confinement enables strong coupling on a single pass (no cavity needed!)
Novel physics in lower dimensions

- Examples of few-particle behavior:
  - Enhancement of spontaneous emission and efficient photon collection
    \[ \Gamma_0 \]
    \[ \Gamma_{1D} \]
    \[ \Gamma_0 \sim \frac{\lambda^2 v_g}{\Lambda c} \]
  - Infinite-range interactions (never lose a photon in pure 1D system)
  - Single-photon blockade

- Use multi-level atom (e.g., lambda system) and external control fields to gain coherent control over these processes
  - Single photons on demand, single-photon transistor, etc...
Possible physical realizations

- **Tapered optical fibers**
  - K. Hakuta (Japan)
  - Typical core diameter: ~100 nm
  - Best possible confinement: ~$(\lambda/n)^2$
  - Max coupling efficiency: < 50%
  - Propagation losses: ☹️
  - Loading cold atoms: ☑️

- **Photonic crystal fibers**
  - Lukin (Harvard) & Vuletic (MIT)
  - Typical core diameter: ~5 µm
  - Best possible confinement: ~$\lambda^2$
  - Max coupling efficiency: < 50%
  - Propagation losses: ☑️
  - Loading cold atoms: ☑️

- **Plasmonics**
  - Lukin & Park (Harvard)
  - Typical core diameter: ~100 nm
  - Best possible confinement: ~$R^2$
  - Max coupling efficiency: >99.9% 😊
  - Propagation losses: 😞
  - Loading cold atoms: ???
Strongly correlated, many-body physics

- In analogy with condensed matter physics:

  \[ \text{Strong interactions} + \text{reduced dimensionality} = \text{interesting physics beyond single-particle behavior} \]

- Can one create strongly correlated, many-body photonic states?
  - Represents quantum optics in its extreme
  - System no longer well-described by the properties of the underlying individual photons

- Issues to address:
  - Physical implementation to realize strongly correlated photons
  - Method to detect strongly correlated states
Engineering coherent atom-photon interactions

- Quantum optical techniques \( \Rightarrow \) manipulate propagation and interaction of photons
- Ideas based on Electromagnetically Induced Transparency (EIT) provide widely tunable system

EIT and dark states

\[
\begin{align*}
H &= \Omega \vert b \rangle \langle c \vert + E \vert b \rangle \langle a \vert + h.c. \\
\vert D \rangle &\sim E \vert c \rangle - \Omega \vert a \rangle \\
H \vert D \rangle &= 0
\end{align*}
\]

- Dark state D decoupled from excited state – no absorption of E on resonance
- Effect of quantum coherence and interference
Electromagnetically induced transparency

- Slow light and dark-state polaritons
- Control field creates “transparency window”
- Steep change in refractive index $\rightarrow$ slow group velocity
- Probe field propagates with minimal distortion and variable group velocity
- Control field mixes photonic component and atomic spin coherence wave

$$\left(\frac{\partial}{\partial z} + \frac{1}{v_g(t) \frac{\partial}{\partial t}}\right)\psi(z,t) \approx 0$$

$$v_g \approx \frac{\Omega^2(t)}{\Gamma_{1D} n_z}$$
Engineering an effective mass

- Add one-photon detuning $\Rightarrow$ shift absorption resonances

- Curvature of susceptibility causes pulse distortion $\Rightarrow$ tunable effective mass

- In principle, even higher order corrections exist
  - Can always check to see that these corrections are irrelevant

\[ \Omega(t) \quad \begin{array}{c} \Delta_0 \end{array} \quad \{ \begin{array}{c} |b\rangle \\
|c\rangle \end{array} \quad |a\rangle \]

\[ d^2\chi / d\omega^2 \neq 0 \]
Photon nonlinearities with EIT

Early ideas – Imamoglu (1997), Andre et al. (2005)
Level shifts $\Rightarrow$ intensity-dependent change in refractive index

Can achieve resonantly-enhanced nonlinearities with low losses

$$i\frac{\partial}{\partial t}\psi \sim g|\psi|^2\psi, \quad g = \frac{\Gamma_{1D}v_g}{\Delta_p}$$

tunable!!!
Photon trapping techniques

- Add a standing wave control field

\[ \begin{align*}
\Delta_p & \left\{ \begin{array}{c}
\Delta_0 \\
\Omega(t)
\end{array} \right\} \rangle \left\{ \begin{array}{c}
|b\rangle \\
|a\rangle
\end{array} \right\}
\]

- No EIT in nodes \(\Rightarrow\) periodic absorptive profile \(\Rightarrow\) Bragg grating!
- Probe field trapped by tiny “mirrors”

- Left- and right-propagating polaritons become coupled (cf. cavity)
- Photonic component also forms nodes (pulse matching)
- Trapping \(\Rightarrow\) longer interaction times!
Nonlinear Schrodinger equation for photons

- Full dynamics of system given by 1-D nonlinear Schrodinger equation

\[ i\partial_t \Psi(z, t) = -\frac{1}{2m_{\text{eff}}} \partial_z^2 \Psi(z, t) + 2\tilde{g}\Psi(z, t)\Psi^*(z, t), \]

- Condensed matter \(\rightarrow\) strongly correlated states are possible (Tonks-Girardeau gas)

- When interactions becomes “large”, photons behave as impenetrable particles and “fermionize”

interaction parameter

\[ \gamma = \frac{I}{K} \approx \frac{gm}{n_{ph}} \]

“crystal” correlations – gain knowledge about positions of other photons from knowing that of one photon

\[ g^{(2)}(z, z' = 0) \]

anti-bunching
Preparing and detecting a TG gas of photons

- Take advantage of system tunability
- Loading of pulse

Coherent (classical) pulse $E$

$\Omega_+(t)$
Preparing and detecting a TG gas of photons

- Take advantage of system tunability
- Loading of pulse

\[ \Omega_+(t) \]
Preparing and detecting a TG gas of photons

- Take advantage of system tunability
- Loading of pulse

\[ \Omega_+ (t) \]
Preparing and detecting a TG gas of photons

- Take advantage of system tunability
- Loading of pulse

\[ \Omega_+ (t) \]
Preparing and detecting a TG gas of photons

- Take advantage of system tunability

- Trapping of pulse
Preparing and detecting a TG gas of photons

- Take advantage of system tunability
- Controlled evolution under NLSE

\[ \gamma(t) \]

\[ \Delta_p(t), \Delta_0(t) \]

\[ \Omega_+(t), \Omega_-(t) \]
Preparing and detecting a TG gas of photons

- Take advantage of system tunability
- Readout of pulse

\[ \Omega_+(t) \]

- Spatial correlations of trapped pulse  ↔  temporal correlations of exiting pulse
TG gas of photons

- Preparation of strongly correlated photons is non-equilibrium process
- For photonic systems, one must determine conditions to end up near the final state of interest
  - For TG gas, want to observe anti-bunching and crystal correlations
- Relevant processes:

\[ \gamma(t) \]

- Expansion of pulse during evolution
- Free or hydrodynamic expansion
- Hardcore bosons released from trap
- Rigol & Muramatsu (2005), Minguzzi & Gangardt (2005)
TG gas of photons

- Preparation of strongly correlated photons is non-equilibrium process
- For photonic systems, one must determine conditions to end up near the final state of interest
  - For TG gas, want to observe anti-bunching and crystal correlations
- Relevant processes:

\[ \frac{\partial \mu}{\partial t} = \mu^2 \]

“Ideal” correlation functions for distances < healing length

Expansion of pulse during evolution

Hardcore bosons released from trap
Rigol & Muramatsu (2005), Minguzzi & Gangardt (2005)

Diabatic

Adiabatic

Free or hydrodynamic expansion
TG gas of photons

- Preparation of strongly correlated photons is non-equilibrium process
- For photonic systems, one must determine conditions to end up near the final state of interest
  - For TG gas, want to observe anti-bunching and crystal correlations
- Relevant processes:
  - Expansion of pulse during evolution
  - “Ideal” correlation functions for distances < healing length
  - Diabatic
  - Adiabatic
  - Free or hydrodynamic expansion
  - Hardcore bosons released from trap
  - Rigol & Muramatsu (2005), Minguzzi & Gangardt (2005)
- Photon losses (finite transparency window)
Experimental parameters

- Requirements for observing a TG gas and crystal correlations
  - N=10 photons

OD of 1000 and 30% coupling efficiency gives $\gamma=10$
Outlook

- Combining quantum optical techniques and novel technologies enables new optical physics and creation of strongly correlated, many-body photon gases
- Interesting correlations can be probed by standard quantum optical techniques
- Applications in areas such as quantum information and metrology
- New connections between optical and condensed matter physics
- Can exploit photon polarization, diversity of atomic level structure, and tunability to realize even more exotic systems
- Use light to simulate matter Hamiltonians