Ultrastrong spin-motion coupling in nanofiber-based optical traps

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Nanofiber-based optical traps

Optical nanofiber

- 500 nm
- 125 µm
- evanescent light field

Trapping atoms

- atom (cesium)
- red detuned light (1064 nm, attractive)
- blue detuned light (783 nm, repulsive)

key points:

- light-assisted collisions during loading → max. 1 atom / site
- typically: $N = 10^2 - 10^3$ atoms
  $\text{OD} = 1 - 10$

[Vetsch et al., PRL 104, 203603 (2010)]
Trapping atoms in evanescent light fields

Fictitious magnetic field! \([\text{Cohen-Tannoudji & Dupont-Roc, } PRA 5, 968 (1972)]\]

\[ \hat{V}_{\text{vec}} = g_F \mu_B B_{\text{fict}} \cdot \hat{F} \]

depends on the atom’s spin state

\[ \hat{V}_{\text{vec}} \propto \alpha_v(\omega) (\mathcal{E}^* \times \mathcal{E}) \cdot \hat{F} \]

With our trap configuration, to first order: linear gradient

nanofiber

\[ B_{\text{fict}} \approx b_y \times y e_x \]

\[ 1.3 \text{ G.} \mu\text{m}^{-1} \]
What is the effect on the atoms?

Spin-motion coupling

« natural » quantization axis

\[
\begin{align*}
\hat{y} &= y_0 (\hat{a} + \hat{a}^\dagger) \\
\hat{F}_x &= \frac{1}{2} (\hat{F}_+ + \hat{F}_-) \\
\hat{F}_\pm |m_y\rangle &\propto |m_y \pm 1\rangle
\end{align*}
\]

(Cesium, F=4)

atoms in nanofiber based optical trap

\[
\begin{align*}
\hat{H} &= \hbar \omega \hat{a}^\dagger \hat{a} + g_F \mu_B \left( B_0 \hat{F}_y + b_y \hat{y} \otimes \hat{F}_x \right) \\
\hat{H} &= \hbar \omega \hat{a}^\dagger \hat{a} + \hbar \alpha_F B_0 \hat{F}_y + \hbar g (\hat{a} + \hat{a}^\dagger) (\hat{F}_+ + \hat{F}_-)
\end{align*}
\]

(CQED model(s) (Jaynes-Cummings/Dicke))

harmonic oscillator

Zeeman shift

« spin-motion » coupling

quantized light field (in cavity)

N-level system (atom[s])

Atom-light coupling

[Schneeweiss, Dareau & Sayrin, PRA 98, 021801(R) (2018)]
Looking for an experimental signature...

Our probe: fluorescence spectroscopy

- heterodyne detection
- power spectral density (PSD) yields energy spectrum

\[ \hbar \omega_S = \hbar \omega_i - \Delta E \]

For off-resonant spin-motion coupling → yields trap frequencies

(transitions from ground state to first excited motional states)
Experimental signature of the spin-motion coupling!

**off-resonant coupling**

- Motional state
- $n_y = 1$
- $n_y = 0$
- $m_F = -4$
- $m_F = -3$
- $\omega_y$
- $\Delta E \propto B_0$

**resonant coupling → vacuum Rabi splitting**

- Rabi frequency
- $n_y = 1$
- $n_y = 0$
- $m_F = -4$
- $m_F = -3$
- $|+\rangle$
- $|-\rangle$
- $|0\rangle$
- $|0\rangle \rightarrow |-\rangle$
- $|0\rangle \rightarrow |+\rangle$
- $|-\rangle \rightarrow |+\rangle$
- $|+\rangle \rightarrow |-\rangle$

Graphs showing PSD (a.u.) vs. detuning (kHz) for both cases.
Experimental signature of the spin-motion coupling!

Scanning across resonance

[Dareau et al., PRL 121, 253603 (2018)]

Trap frequencies

\[
\begin{align*}
    f_x &= 149(2) \text{ kHz} \\
    f_y &= 93(2) \text{ kHz} \\
    f_z &= 243(5) \text{ kHz}
\end{align*}
\]

Rabi frequency

(for n=1)

\[
\begin{align*}
    \Omega_x &= 2n \times 35(1) \text{ kHz} \\
    \Omega_y &= 2n \times 36(1) \text{ kHz}
\end{align*}
\]

\(\Omega_x / \omega_x = 0.24(2)\)

\(\Omega_y / \omega_y = 0.38(2)\)

possible to increase coupling strength even further
(e.g. in optical lattices)

[Schneeweiss et al., PRA 98, 021801(R) (2018)]
Tuning the coupling strength

**Idea**: compensate the vector ac Stark shift using fiber-guided laser at the “tune-out” wavelength ($\lambda=880$ nm)

- Scalar polarizability vanishes
  - Do not affect scalar trapping potential
  - “Pure” fictitious magnetic field

**Experiment**: reduction of vacuum Rabi splitting

Looking at direct transitions between excited dressed states yields Rabi splitting.

Rabi splitting decreases when tune-out laser power increases.

Total compensation at ~ $400\mu$W
Conclusion & outlook

Ultra-strong spin-motion coupling

- naturally present in nanofiber-based optical traps (& in optical microtraps)
- possible to tune with additional light field
- analogy with CQED (Jaynes-Cummings / Dicke)

Outlook: tunability

- increase coupling strength
  - “deep-strong coupling regime” (coupling $>\omega_t$)
- dynamical tuning / quenches
  - $\Omega(t)$ with variation faster than trap oscillation period.
  - Dynamical Casimir effect?

Outlook: CQED

- increase coupling strength
  - Dicke model ($F=4 \rightarrow N=8$ atoms)
- Phase transition in the “mesoscopic” regime ($N < \infty$)?

Note: also in optical lattices $\gg$ Schneeweiss et al., PRA 98, 021801(R) (2018)
Thank you for your attention!

Slides available on www.adphys.eu

References:

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