Laser applications to the study of atomic quantum structure.

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Luis A. Orozco
www.jqi.umd.edu
Plan of the course:

1st lecture: Introduction to the interaction of light with atoms, (nanofibers).

2nd lecture: Atom-light interaction of a two level atom (nanofibers at low intensity).

3rd lecture: Atom-light interaction of a two level atom at high intensity (cavity QED).

4th lecture: Different types of laser traps for atoms, (nanofibers, cavity QED, and spectroscopy).

5th lecture: Weak interaction studies with Fr, a proposal.
The $\text{HE}_{11}$ mode of the nanofiber with linearly polarized light
Radius \sim 250 \text{ nm}; \text{ Decay length:} \lambda/2\pi \sim 100 \text{ nm}
$\sin \theta = \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2}$

$V$ is related to the acceptance angle and the radius $R$ of the fiber.

$V = \frac{2\pi R}{\lambda} \sqrt{n_1^2 - n_2^2}$

2nd lecture: Atom-light interaction of a two level atom (nanofibers [ONF]).
1. One atom interacting with light in free space.
Absorption and Stimulated Emission are time reversals of each other, you can say this is the classical part. Spontaneous emission is the quantum, that is the jump.
Saturation intensity:
One photon every two lifetimes over the cross section of the atom (resonant)

\[ I_0 = \frac{\hbar \omega_0}{2 \tau_0 \sigma_0} = \frac{\pi \gamma_0 \hbar \omega_0}{3 \lambda_0^2} \]

This makes the rate of spontaneous emission equal to the stimulated emission (Rabi Frequency \( \Omega \)) and the population on the excited state \( m = 1/4 \).

\[ \Omega = \frac{\vec{d} \cdot \vec{E}}{\hbar} = \gamma \sqrt{\frac{I}{I_0}} \]

\[ m = \frac{1}{2} \frac{I}{I_0} + \frac{I}{I_0} \]
At low intensity ($I << I_0$) only spontaneous emission is relevant.
How to measure the rate of spontaneous emission?
Measure the lifetime when $I \ll I_0$
Method:
Start a clock when the light turns off and then stop the clock when a photon arrives at the detector. Time Correlated Single Photon Counting (TCSPC)

What is the probability of detecting a photon after we have excited the system, an exponential decay.
Free space atoms

Counts for Curve c

Counts for Curves a, b

First point of fit

(Residuals)/σ

Time (ns)
### Francium D$_1$ Line

**Final number:** 29.45 (11) nm


<table>
<thead>
<tr>
<th>Error</th>
<th>Fr $P_{3/2}(%)$</th>
<th>Fr $P_{1/2}(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systematic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAC-MCA nonlinearity</td>
<td>±0.03</td>
<td>±0.03</td>
</tr>
<tr>
<td>Time calibration</td>
<td>±0.04</td>
<td>±0.04</td>
</tr>
<tr>
<td>Truncation error</td>
<td>±0.39</td>
<td>±0.19</td>
</tr>
<tr>
<td>Zeeman quantum beat</td>
<td>±0.04</td>
<td>±0.00</td>
</tr>
<tr>
<td>Other</td>
<td>±0.23</td>
<td>±0.25</td>
</tr>
<tr>
<td>Total systematic</td>
<td>±0.46</td>
<td>±0.32</td>
</tr>
<tr>
<td>Statistical</td>
<td>±0.24</td>
<td>±0.18</td>
</tr>
<tr>
<td>Sum in quadrature</td>
<td>±0.52</td>
<td>±0.37</td>
</tr>
</tbody>
</table>

**TABLE I.** Error budget for the lifetimes of the $D_2$ and $D_1$ lines of Fr in percentage.
2. One atom interacting with light near a nanofiber, Purcell effect.
Optical Nanofibers

unmodified fiber
taper (~2.5 cm)
waist (mm - cm)

$\varnothing \approx 125\mu m$

$\varnothing \approx 500nm$
Optical Nanofibers

$\lambda = 780 \, \text{nm}$
Modified decay rate

\[
\frac{\gamma' (r)}{\gamma_0} = \frac{\gamma_{rad} (r)}{\gamma_0} + \frac{\gamma_{1D} (r)}{\gamma_0}
\]

Proportional to the electric field of the radiated mode.
Effect of a dielectric surface

Region 1

\(\epsilon_1\)

\(d\)

Region 2

\(\epsilon_2\)

Induced Dipoles (images)
Effect of a dielectric surface

Atom–Surface Distance in units of $\lambda$

$\tau_{\parallel}$

$\tau_{\perp}$
Effect of a dielectric surface

Region 1
\[ \epsilon_1 \]

Region 2
\[ \epsilon_2 \]

Reflection on the second surface.
Purcell effect around an ONF
Purcell effect around an ONF
Purcell effect around an ONF
Use free atoms around the nanofiber, distribution peaks around 70 nmm from density, mode and Van der Walls interaction

\[ \rho(r), p_{abs}(r), \alpha(r) \text{ (arb. units)} \]
Dipole orientation

 Probe

 Vertically Polarized

 Horizontally Polarized

 Nanofiber

 Atomic Dipoles

 Polarization of the probe (H)
Dipole orientation

Nanofiber

Atomic Dipoles

Vertically Polarized

Probe

Polarization of the probe (V)
Free Space
Probe Vertically Polarized

Probe Horizontally Polarized

Nanofiber Atomic Dipoles

$\log_{10}$ of the counts rate

time (ns)
Probe Verticaly Polarized

Probe Horizontally Polarized

Nanofiber

Atomic Dipoles

Log\(_{10}\) of the counts rate

time (ns)
Measured decay rates (one atom)

- **V polarized probe**
- **H polarized probe**

**Nanofiber**

**Atomic Dipoles**
Measured decay rates (one atom)

\[ \gamma / \gamma_0 \]

V polarized probe
H polarized probe

Nanofiber
Atomic Dipoles

Probe vertically polarized
Probe horizontally polarized
3. Many atoms interacting with light (decay) near an ONF. Super- and sub-radiance.
Super- and Sub-radiance
(a classical explanation)

“When two organ pipes of the same pitch stand side by side, complications ensue which not infrequently give trouble in practice. In extreme cases the pipes may almost reduce one another to silence. Even when the mutual influence is more moderate, it may still go so far as to cause the pipes to speak in absolute unison, in spite of inevitable small differences.

Lord Rayleigh (1877) in "The Theory of Sound".
Super- and Sub-radiance
(a classical explanation)

We need the response of one oscillator due to a nearby oscillator (interference):

\[
\ddot{x}_1 + \gamma_0 \dot{x}_1 + \omega_0^2 x_1 = \frac{3}{2} \omega_0 \gamma_0 \hat{d}_1 \cdot \vec{E}_2 (\vec{r}) x_1,
\]

assuming \( x_1 = x_{10} \exp(i(\omega - i\gamma/2)t) \)

\[
\gamma = \gamma_0 + \frac{3}{2} \gamma_0 \text{Im} \left\{ \hat{d}_1 \cdot \vec{E}_2 (\vec{r}) \right\}, \quad \text{with} \quad \left| \hat{d}_1 \cdot \vec{E}_2 (0) \right| = \frac{2}{3}
\]

\[
\omega = \omega_0 - \frac{3}{4} \gamma_0 \text{Re} \left\{ \hat{d}_1 \cdot \vec{E}_2 (\vec{r}) \right\}
\]
Super- and Sub-radiance
(a classical explanation)

\[ P = \frac{\varepsilon}{\Delta t} = IA \Rightarrow \Delta t = \frac{\varepsilon}{IA} \]

For N dipoles \( \varepsilon \Rightarrow N\varepsilon \)
Super- and Sub-radiance
(a classical explanation)

Normal radiance

\[ I = |E_0|^2 = I_0 \]

\[ \Delta t = \tau_0 \]
Super- and Sub-radiance
(a classical explanation)

Normal radiance  Super-radiance

\[ I = |E_0|^2 = I_0 \]
\[ \Delta t = \tau_0 \]

\[ I = 4I_0 \]
\[ \Delta t = \frac{1}{2}\tau_0 \]
Super- and Sub-radiance
(a classical explanation)

Normal radiance

Super-radiance

Sub-radiance

\[
\begin{align*}
I &= |E_0|^2 = I_0 \\
\Delta t &= \tau_0 \\
\Re \{E\} &\quad \Im \{E\}
\end{align*}
\]

\[
\begin{align*}
I &= 4I_0 \\
\Delta t &= \frac{1}{2}\tau_0 \\
\Re \{E\} &\quad \Im \{E\}
\end{align*}
\]

\[
\begin{align*}
I &= 0 \\
\Delta t &= \infty \\
\Re \{E\} &\quad \Im \{E\}
\end{align*}
\]
Super- and Sub-radiance
(a classical explanation)

Normal radiance  Super-radiance  Sub-radiance

\[ \Delta t = \tau_0 \]
\[ \Delta t = \frac{1}{2} \tau_0 \]
\[ \Delta t = \infty \]
Super- and Sub-radiance
(a classical explanation)

Super-radiance

Sub-radiance

Super- and sub-radiance are interference effects!

\[ \Delta t = \frac{1}{2} \tau_0 \]

\[ \Delta t = \infty \]
Interacting dipoles
Interacting dipoles

\[ U_{\text{free}} \propto \frac{\exp(ikr)}{kr} \]

\[ \Omega_{12} \propto \cos kr \]

\[ \gamma_{12} \propto \frac{\sin kr}{kr} \]
Interacting dipoles

\[ U_{\text{free}} \propto \frac{\exp(ikr)}{kr} \]

\[ \Omega_{12} \propto \frac{\cos kr}{kr} \]

\[ \gamma_{12} \propto \frac{\sin kr}{kr} \]

If the atoms are too close this diverges.

If the atoms are too far this goes to zero.
The atoms have to be near, but not too near which limits $N$.

$$
U_{\text{free}} \propto \frac{\exp(ikr)}{kr}
$$

$$
\Omega_{12} \propto \frac{\cos kr}{kr}
$$

$$
\gamma_{12} \propto \frac{\sin kr}{kr}
$$
Observation of infinite-range interactions
Infinite Range Interactions

Not to scale
Infinite Range Interactions
Infinite Range Interactions

Not to scale
The limit is now how many atoms can we put within the coherence length associated with the spontaneous emission.
Long distance modification of the atomic radiation
Long distance modification of the atomic radiation

We have atomic densities low enough to observe mostly infinite-range interactions
Experimental idea
The idea behind the experiment
The idea behind the experiment

We look for modifications of the radiative lifetime of an ensemble of atoms around the ONF.
The idea behind the experiment

The sub- and super-radiant behavior depend on the phase relation of the atomic dipoles along the common mode.
Measuring the Radiative Lifetime
Measuring the Radiative Lifetime
Atomic distribution with optical pumping
Two distinct lifetimes
Two distinct lifetimes

\[ \tau \approx 0.9\tau_0 \]

\[ \tau \approx 7.7\tau_0 \]
Two distinct lifetimes

\[ \tau \approx 0.9 \tau_0 \]

\[ \tau \approx 7.7 \tau_0 \]
Decay time vs detuning

No radiation trapping for long lifetime
Decay time vs detuning

No radiation trapping for short lifetime
Pulse and signal

Log\textsubscript{10} normalized count rate

time (in units of $\tau_0$)
Two distinct lifetimes

\[ \tau \approx 0.9 \tau_0 \]

\[ \tau \approx 7.7 \tau_0 \]
$N$ dependence

\[ \gamma_{\text{sup}} = \gamma_{\text{rad}} + N \gamma_{1D} \]
Superradiance depends on the atom number!
Measurement of $N$

Transmission

$OD = N \cdot OD_1(\vec{r}_0)$
The slope (0.02) is smaller than $\gamma_{1D} (0.10)$ because it is an average over different realizations, not all of them superradiant.
Sub-radiance???

\[ \gamma_{\text{sup}} = \gamma_{\text{rad}} + N \gamma_{1D} \]
Infinite-range subradiance is limited!

\[ \gamma_{\text{sup}} = \gamma_{\text{rad}} + N\gamma_{1D} \]

\[ \gamma_{\text{sub}} = \gamma_{\text{rad}} - \gamma_{1D} \]

Infinite-range subradiance is limited!
Sub-radiance???

\[ \gamma_{rad} \]

\[ \gamma_{1D} \]

\[ \gamma_{sub} = \gamma_{rad} - \gamma_{1D} \approx 0.9 \gamma_0 \]

The subradiant decay rate we measure is too slow!
Understanding the Signal
Understanding the Signal

(a)

(b) \(\gamma_{12}^{(\text{rad})}/\gamma_0\)

(c) \(\gamma_{12}^{(1D)}/\gamma_{1D}\)

\[\Delta \phi\]

[Color scale legend from 1.0 to -1.0]
Polarization dependent signal

Vertically polarized probe

Horizontally polarized probe
Polarization dependent signal

Vertically polarized probe

Horizontally polarized probe
- Interaction distance smaller than $\lambda$: all modes get cancelled.

- Interaction distance greater than $\lambda$: only one mode gets cancelled

\[
\gamma_{sub} = \gamma_{rad} - \gamma_{1D} \approx 0.9\gamma_0
\]

We measure

\[
\gamma_{sub} = 0.13\gamma_0
\]
Super-radiant Signal

- Interaction distance smaller than $\lambda$: all modes get enhanced.
- Interaction distance greater than $\lambda$: only one mode gets enhanced.

\[
\gamma_{\text{sup}} = \gamma_{\text{rad}} + N \gamma_{1D}
\]

We measure
\[
\gamma_{\text{sup}} = 1.1 \gamma_0
\]
Fitting the Simulation

(a) 

(b) 

Normalized Residuals

Log_{10} normalized count rate

Log_{10} normalized count rate

Normalized Residuals
Fitting the Simulation

Average number of atoms

$\frac{\gamma}{\gamma_0}$

Optical density
Can we see a collective atomic effect of atoms around the nanofiber?
Long distance modification of the atomic radiation
Long distance modification of the atomic radiation

We have atomic densities low enough to observe mostly infinite-range interactions
Splitting the MOT in two

\[ \approx 400 \lambda \]
Evidence of infinite-range interactions
Two distinct lifetimes

\[ \tau \approx 0.9\tau_0 \]

\[ \tau \approx 7.7\tau_0 \]
Summary:
1. Spontaneous emission vs stimulated emission.
2. Spontaneous emission of one atom near a nanofiber.
3. Collective effects through super- and sub-radiance through a nanofiber.
Gracias