Modeling the two-quantum coherent spectrum of a semiconductor microcavity

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About Me

- 2023 Graduate
  - B.S. Space Physics, Minor Computer Science
  - ERAU (Prescott)
  - Gravitational Theory
- 2x SPS Intern
  - SOCK
  - NIST Research
- Served on SPS National Council 2 years
  - AZC Zone 16
- NASA Starshade Program
- Love to read
Our Project

- Multidimensional Spectroscopy
  - Light-matter interactions
  - Analyzing excitonic spectra
- Gallium Arsenide Nanostructure Semiconductor
  - Many-body interaction inside cavity
Our Goal

Simulate a 2-Quantum Spectra to compare with Experimental results

Our Approach

- Polariton Basis
  - Double-Sided Feynman Diagrams
The Details

The "-itons"
- Polariton: Combination of a photon and an exciton
- Exciton: Combination of an electron and a hole
- Biexciton: 2 X Exciton

What's happening in the lab?
- Short pulses excite sample
- Set of nested interferometers
- Isolates the nonlinear response
- Multiple time delays -> multiple spectral dimension
- Linear v. Nonlinear

What We Saw
- LP/UP Spectra
- Needed a theoretical model to compare our findings based on various parameters
Experimental Spectra

Scan 30: 2Q Cocircular - \( \Delta \approx -2.12 \text{ meV} \)
Experimental Spectra

Scan 30: 2Q Cocircular - $\Delta \sim 2.12$ meV

- 2UP
- 2LP
Experimental Spectra

Scan 30: 2Q Cocircular - $\Delta \sim -2.12$ meV

Absorption energy (meV)

Emission energy (meV)

2LP

2UP

LP-UP

UP-LP
Diagonalization

- Diagonalize the Jaynes-Cummings Hamiltonian:

\[
\hat{H}_{JC} = \tilde{\omega}_a \hat{\sigma}^+ \hat{\sigma}^- + \tilde{\omega}_c \hat{a}^{\dagger} \hat{a} + g_1 (\hat{a}^{\dagger} \hat{\sigma}^- + \hat{a} \hat{\sigma}^+) 
\]

\[
\lambda_1, \lambda_2 = \frac{-E_x + E_c \pm \sqrt{(E_x + E_c)^2 - 4(E_c E_x - g^2)}}{2} 
\]

\[
\lambda_1, \lambda_2 = \frac{2E_x + \delta \pm \sqrt{\delta^2 + \Omega}}{2} 
\]

- Plot \( \lambda \) as a function of \( \delta \)
Level Scheme Diagram

2UP
2MP
2LP
UP
LP

f "Two-Quantum"

e "One-Quantum"

g
Level Scheme Diagram

2UP

2MP

2LP

UP

LP

f "Two-Quantum"

e "One-Quantum"

g
Level Scheme Diagram

NIST Nanoscale Spectroscopy
**An example (2 quantum):**

- Each element of the diagram tells us a different part of the equation
- Left Line = ket, Right Line = bra
- After various approximations, you can receive an equation like:

\[
P^{(3)}(t) = \mu^* (\varepsilon_1 (T_2 - T_1) e^{-i\omega_{eg} (T_2 - T_1)} + \\
\varepsilon_2 (T_3 - T_2) e^{-i\omega_{fg} (T_3 - T_2)} + \\
\varepsilon_3 (T - T_3) e^{-i\omega_{fe'} (T - T_3)}
\]
2 Quantum Spectra

- Materials Needed:
  - Energy of UP/LP (diagonalization)
  - Level Scheme Diagram
  - 2D Fourier Transform of P(3)
  - Patience
- Figure has modified detuning value = -3
  - Detuning: Moves both peaks around
2 Quantum Spectra

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Adding the Biexciton

- Experimental Data including Biexciton
- A "biexciton" can be added to the simulation
  - Has independent energy
  - Another level on the level scheme diagram
Adding the Biexciton

- A "biexciton" can be added to the simulation
  - Has independent energy
  - Another level on the level scheme diagram
    - Filtered level gives this animation -->
Next Steps

- With the biexciton added, we are close to simulating experimental data
  - Vary our matrix to match peak amplitudes
  - Add parameters or other options to explain "biexciton"

This dark state animation has a fixed detuning of -1
Thank You

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