Electron-FIR photonic transport: High order transitions in artificial atoms coupled to external leads

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Experimental impetus...

nature physics

LETTERS

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Collective non-perturbative coupling of 2D electrons with high-quality-factor terahertz cavity photons

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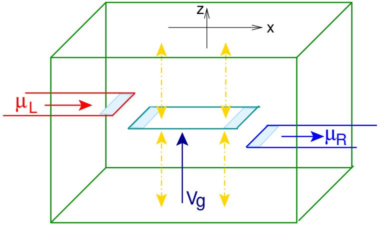
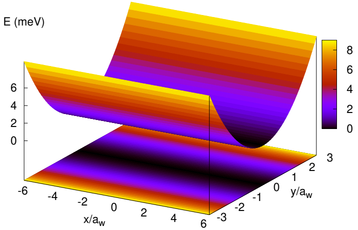
The collective interaction of electrons with light in a high-quality-factor cavity is expected to reveal new quantum phenomena[1–7] and find applications in quantum-enabled technologies[8,9]. However, combining a long electronic coherence time, a large dipole moment, and a high quality-factor has proved difficult[10–13]. Here, we achieved these conditions simultaneously in a two-dimensional electron gas in a high-quality-factor terahertz cavity in a magnetic field. The vacuum Rabi splitting of cyclotron resonance exhibited a square-root dependence on the electron density, evidencing collective interaction. This splitting extended even where the detuning is larger than the resonance frequency. Furthermore, we observed a peak shift due to the normally negligible diamagnetic term in the Hamiltonian. Finally, the high-quality-factor cavity suppressed superradiant cyclotron resonance decay, revealing a narrow intrinsic linewidth of 5.6 GHz. High-quality-factor terahertz cavities will enable new experiments bridging the traditional disciplines of condensed-matter physics and cavity-based quantum optics.

nonresonant matter decay rate, which is usually the decoherence rate in the case of solids. Strong coupling is achieved when the splitting, $2g$, is much larger than the linewidth, $(\kappa+\gamma)/2$, and ultrastrong coupling is achieved when g becomes a considerable fraction of ω_0. The two standard figures of merit to measure the coupling strength are $C \equiv 4g^2/(\kappa\gamma)$ and g/ω_0; here, C is called the cooperativity parameter[18], which is also the determining factor for the onset of optical bistability through resonant absorption saturation[20]. To maximize C and g/ω_0, one should construct a cavity QED set-up that combines a large dipole moment (that is, large g), a small decoherence rate (that is, small γ), a large cavity Q factor (that is, small κ), and a small resonance frequency ω_0.

Group III–V semiconductor quantum wells (QWs) provide one of the cleanest and most tunable solid-state environments with quantum-designable optical properties. Microcavity QW-exciton-polaritons represent a landmark realization of a strongly coupled light–condensed-matter system that exhibits a rich variety of coherent many-body phenomena[21]. However, the large values of ω_0 and relatively small dipole moments for interband transitions make it

We model

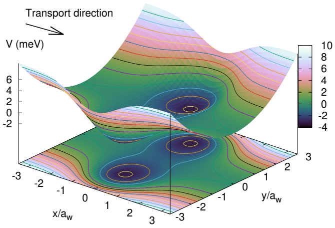




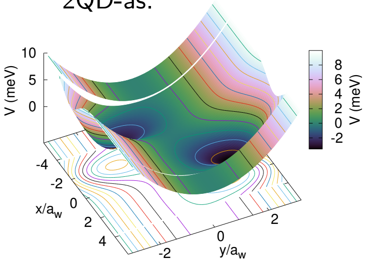
Short quantum GaAs wire in a 3D photon cavity
Weak coupling $g^{\mathrm{L,R}} a_w^{3/2} \sim 0.124 \times (\mathrm{state} - \mathrm{dependence})$ meV
($a_w \approx 23.8$ nm, $B_{\mathrm{ext}} = 0.1$ T)

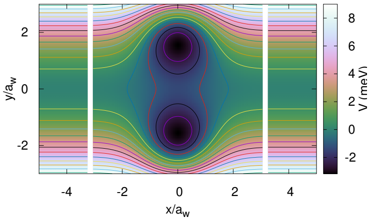
or. . .

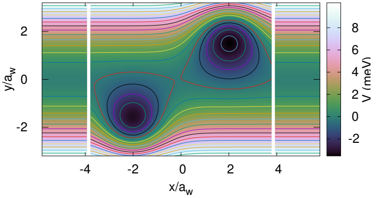
2QD-par.



2QD-as.







Time-dependent transport

$\Downarrow$

Time scales

$\Downarrow$

Transient – intermediate – long time – steady state

$\Uparrow$

Density operator

$\Uparrow$

Open Systems

Equation of motion

Liouville-von Neumann

$$\partial_t W = \mathcal{L}W, \quad \mathcal{L}W = -\frac{i}{\hbar}[H, W]$$

$$H = H_\mathrm{S} + H_\mathrm{LR} + H_\mathrm{T}(t), \quad H_\mathrm{S} = H_\mathrm{e} + H_\mathrm{EM}$$

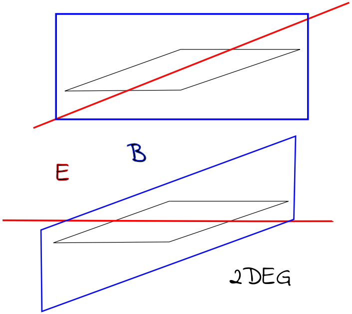
$$H_\mathrm{S} = \int d^2r \psi^\dagger(\mathbf{r}) \left\{ \frac{\pi^2}{2m^*} + V(\mathbf{r}) \right\} \psi(\mathbf{r}) + H_\mathrm{Coul} + \hbar\omega a^\dagger a$$
$$+ \frac{1}{c} \int d^2r \, \mathbf{j}(\mathbf{r}) \cdot \mathbf{A}_\gamma + \frac{e^2}{2m^* c^2} \int d^2r \, \rho(\mathbf{r}) A_\gamma^2$$

$$\boldsymbol{\pi} = \left(\mathbf{p} + \frac{e}{c}\mathbf{A}_\mathrm{ext} \right), \quad \rho = \psi^\dagger \psi, \quad \mathbf{j} = -\frac{e}{2m^*} \left\{ \psi^\dagger \left(\boldsymbol{\pi}\psi \right) + \left(\boldsymbol{\pi}^* \psi^\dagger \right) \psi \right\}$$

Stepwise exact numerical diagonalization, (Fortschritte der Physik 61, 305 (2013))

One quantized cavity mode – no RWA

$$\mathbf{A}(\mathbf{r}) = \begin{pmatrix} \hat{\mathbf{e}}_x \\ \hat{\mathbf{e}}_y \end{pmatrix} \mathcal{A}\left\{a + a^\dagger\right\} \begin{pmatrix} \cos\left(\frac{\pi y}{a_\mathrm{c}}\right) \\ \cos\left(\frac{\pi x}{a_\mathrm{c}}\right) \end{pmatrix} \cos\left(\frac{\pi z}{d_\mathrm{c}}\right), \qquad \begin{matrix} \mathrm{TE}_{011}, & x\text{-pol.} \\ \mathrm{TE}_{101}, & y\text{-pol.} \end{matrix}$$



y-polarization

x-polarization

Projection on the central system

Reduced density operator

$$\rho_{\rm S}(t) = \mathcal{P}W(t) = \rho_{\rm LR}(0){\rm Tr}_{\rm LR}\{W(t)\}$$

Liouville-von Neumann $\Rightarrow$ Nakajima-Zwanzig equation (to 2nd order in $H_{\rm T}$), non-Markovian time-evolution

$$\partial_t\rho_{\rm S}(t) = \mathcal{L}_{\rm S}\rho_{\rm S}(t) + \int_0^t dt' K[t, t-t'; \rho_{\rm S}(t')]$$

with

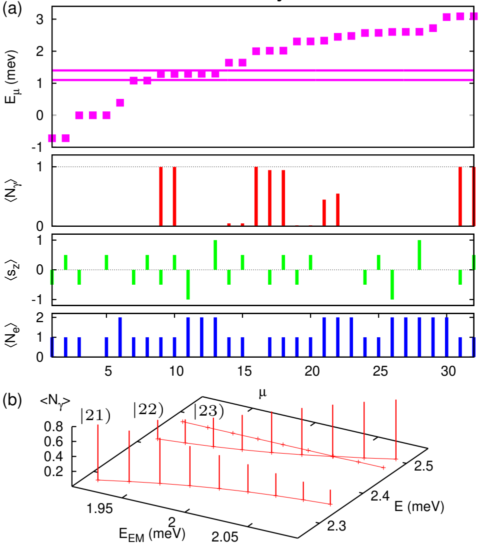
$$K[t, s; \rho_{\rm S}(t')] = {\rm Tr}_{\rm LR}\left\{\left[H_{\rm T}(t), \left[U(s)H_{\rm T}(t')U^{+}(s), \right.\right.\right.$$
$$\left.\left.\left. U_{\rm S}(s)\rho_{\rm S}(t')U_{\rm S}^{+}(s)\rho_{\rm L}\rho_{\rm R}\right]\right]\right\}$$

and

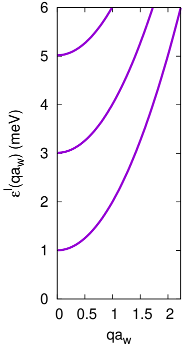
$$H_{\rm T}(t) = \sum_{i,l}\chi(t)\int dq\ \left\{T^l_{qi}c^\dagger_{ql}d_i + (T^l_{qi})^* d^\dagger_i c_{ql}\right\}$$

Spectra of a closed system, y-polarized photons, 2QD-par.

Central system

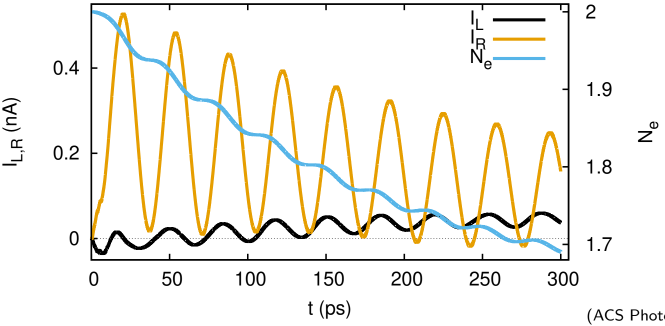


Leads

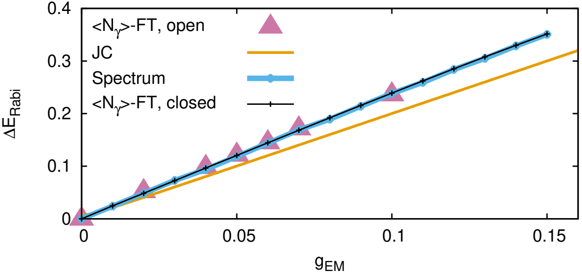


$$\hbar\omega = 2.0 \text{ meV}$$
$$g_{\rm EM} = 0.05 \text{ meV}$$
$$B = 0.1 \text{ T}$$
$$a_w = 23.8 \text{ nm}$$
$$V_g = 0.1 \text{ mV}$$

2 electrons initially, entangled

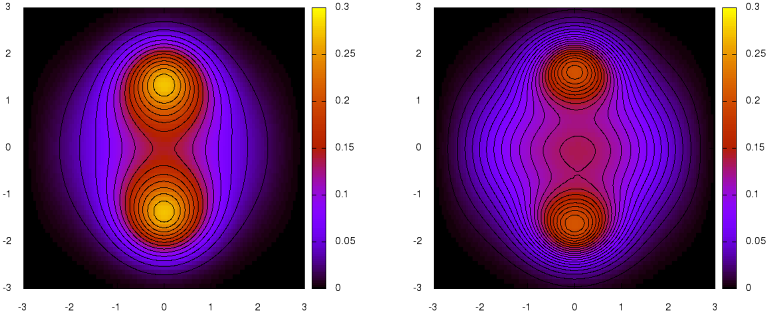


(ACS Photonics 2015, 2, 930 (2015))



Charge density oscillations

$t = 10$ ps $\qquad$ $t = 60$ ps



Variable probability in contact area $\rightarrow$ variable current
$\rightarrow$ Rabi-oscillations detected in transport

Long time evolution

(No memory - Markovian evolution) in many-body Fock space (dim $\sim N$)

$\Downarrow$

Liouville space of transitions (dim $\sim N^2$), (Comp. Phys. Commun. 220, 81 (2017))

$$\partial_t \rho_{\mathrm{S}}^{\mathrm{vec}} = \mathcal{L} \rho_{\mathrm{S}}^{\mathrm{vec}}$$

with solution

$$\rho_{\mathrm{S}}^{\mathrm{vec}}(t) = \left[\mathcal{U} \exp\left(\mathcal{L}_{\mathrm{diag}} t\right) \mathcal{V}\right] \rho_{\mathrm{S}}^{\mathrm{vec}}(0)$$

where

$$\mathcal{L}\mathcal{V} = \mathcal{V}\mathcal{L}_{\mathrm{diag}}, \quad \mathcal{U}\mathcal{L} = \mathcal{L}_{\mathrm{diag}}\mathcal{U}, \quad \mathcal{U}\mathcal{V} = \mathcal{V}\mathcal{U} = \mathcal{I}$$

Steady state can be found as the eigenvalue 0 of

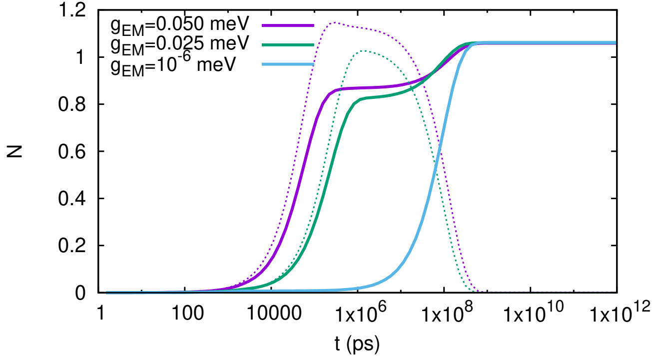
$$0 = \mathcal{L} \rho_{\mathrm{S}}^{\mathrm{vec}}$$

but we use

$$\lim_{t \to \infty} \left[\mathcal{U} \exp\left(\mathcal{L}_{\mathrm{diag}} t\right) \mathcal{V}\right] \rho_{\mathrm{S}}^{\mathrm{vec}}(0)$$

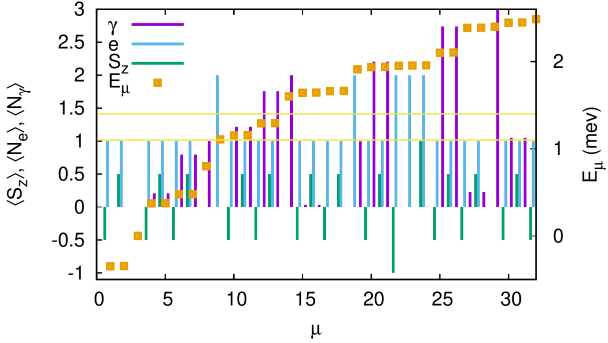
Radiative and nonradiative transitions

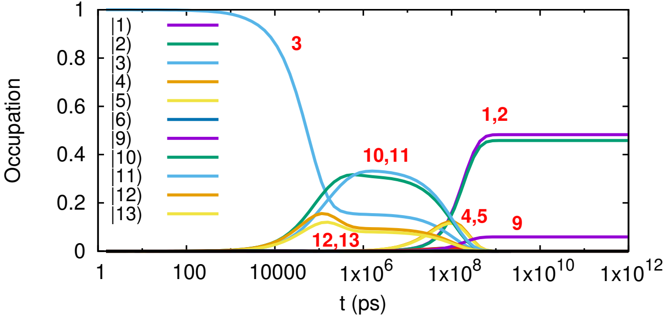
Long time evolution (Annalen der Physik 529, 1600177 (2017)), $\kappa = 0$



No dots, slow charging into Coulomb-blockade regime

Rabi-resonance $\hbar\omega = 0.80$ meV,

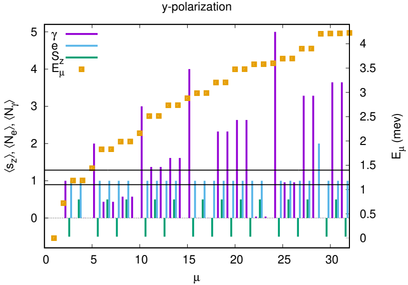

γ
e
Sz
Eμ
⟨Sz⟩, ⟨Ne⟩, ⟨Nγ⟩
Eμ (mev)
μ
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
5
10
15
20
25
30

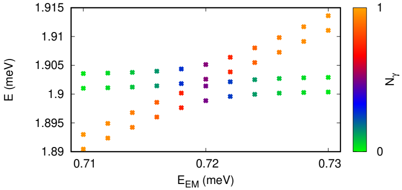

|1)
|2)
|3)
|4)
|5)
|6)
|9)
|10)
|11)
|12)
|13)
3
10,11
1,2
4,5
9
12,13
Occupation
t (ps)
1
0.8
0.6
0.4
0.2
0
1
100
10000
1x10^6
1x10^8
1x10^10
1x10^12

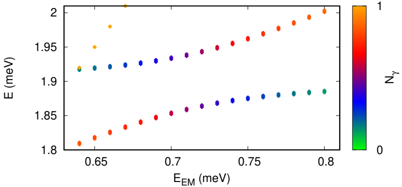
Two types of Rabi resonances, 2QD-par.

(Annalen der Physik 530, 1700334 (2018)), (Physics Letters A 382, 1672 (2018))

$\hbar\omega = 0.72$ meV







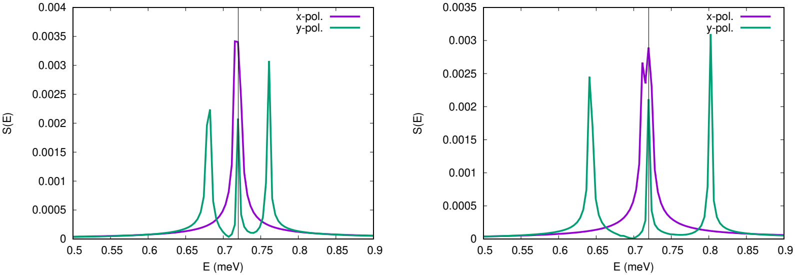
Symmetry selection

Diamagnetic int. $\sim \rho A^2$, x-pol.

Paramagnetic int. $\sim \mathbf{j} \cdot \mathbf{A}$, y-pol.

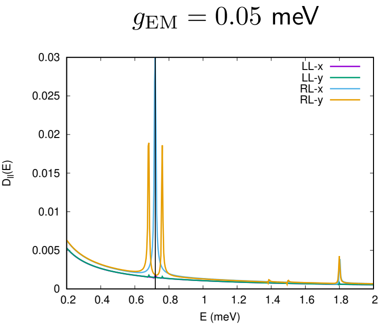
Ground state electroluminescence

(Annalen der Physik 530, 1700334 (2018)), $\kappa = 10^{-3}$ meV



Spectral density, emitted radiation, Mollow triplet. . .
(Also the more complex 2e ground state)

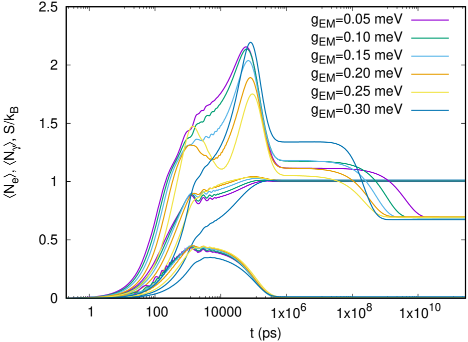
Current correlations

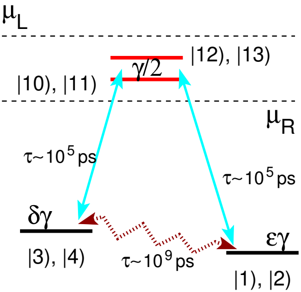


Current noise power spectra for ground state electroluminescence
No Coulomb blockade, $1/f\ldots$

(Physics Letters A 382, 1672 (2018))

Slow interdot ground state transition, 2QD-as

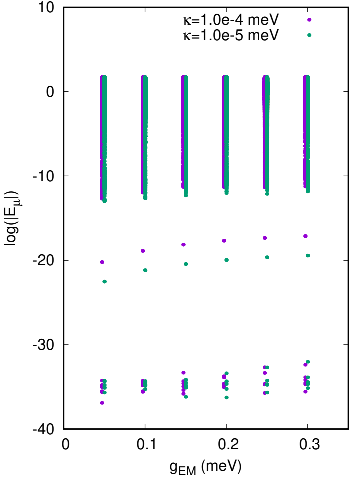




$\hbar\omega = 1.75$ meV, $\kappa = 10^{-5}$ meV

(Annalen der Physik 531, 1900306 (2019))

Exact matrix elements for e-EM-interactions, 2QD-as.



Complex Liouvillian spectrum

Extreme slow interdot ground state transition out of resonance, $\hbar\omega = 1.75$ meV

(Annalen der Physik 531, 1900306 (2019))

Purcel effect seen in transport current: (Nanomaterials 9, 1023 (2019))

Quantum self-induction in transport: (Physica E 127, 114544 (2021))

Summary

- Time-dependent many-body approach
- Central system: Exact interactions
- Shape – geometry
- Weak coupling to external reservoirs
- All time scales
- Effective parallelism, CPU-GPU
- Review: *Entropy* **21**, 731 (2019)

- Andrei Manolescu (RU)
- Valeriu Moldoveanu (NIMP)
- Nzar Rauf Abdullah (US, KUST)
- Chi-Shung Tang (NUU)
- Shi-Sheng Goan (NTU)

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