Spin configuration of an array of quantum rings controlled by cavity photons

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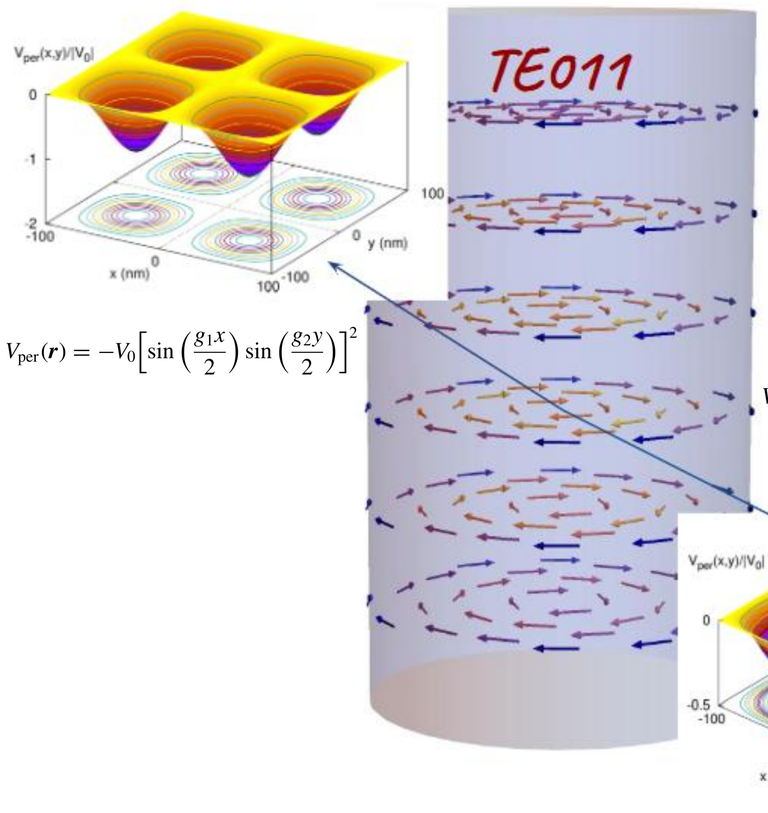
Vidar Gudmundsson, Vram Mughnetsyan, Hsi-Sheng Goan, Jeng-Da Chai, Nzar Rauf Abdullah, Chi-Shung Tang, Valeriu Moldoveanu, and Andrei Manolescu, Phys. Rev. B 111, 115304.

Beyond their technological impact, 2D electron systems in semiconductor heterostructures provide a versatile platform for studying quantum many-body effects. A key feature is the ability to modulate the electron density into quasi-2D or 1D arrays, leading to rich physics. Embedding such systems in photon cavities allows tunable control over electronic and material properties in chemistry, physics, and materials science. The high polarizability and mobility of EGs in GaAs make them ideal for exploring strong coupling with far-infrared photons. We have modeled a change in spin configuration in a 2D square array of quantum rings subjected to a transverse magnetic field. The system is placed in a cylindrical far-infrared photon cavity with a circularly symmetric mode. Our simulations show that spin ordering in each quantum ring can be controlled by the electron-photon coupling strength and photon energy. Electron-electron interactions are treated within a spin-density functional framework, while para- and diamagnetic electron-photon couplings are handled using a configuration interaction approach in a truncated many-body time-dependent coupling scheme that enhances the diamagnetic interaction.

SYSTEM



$$V_{\rm per}(\boldsymbol{r}) = -V_0\left[\sin\left(\frac{g_1 x}{2}\right)\sin\left(\frac{g_2 y}{2}\right)\right]^2$$

$$V_{\rm per}(\boldsymbol{r}) = -V_0\left[\sin\left(\frac{g_1 x}{2}\right)\sin\left(\frac{g_2 y}{2}\right)\right]^2 + V_0\left[\sin\left(\frac{g_1 x}{2}\right)\sin\left(\frac{g_2 y}{2}\right)\right]^4$$

METHODOLOGY

QED - DFT - TP

J. Malave, et al., J. Chem. Phys. 157, 194106 (2022).

$$H = H_{\rm e} + H_{\rm int} + H_\gamma \qquad H_{\rm e} = H_0 + H_{\rm Zee} + V_{\rm H} + V_{\rm per} + V_{\rm xc}$$

$$V_{\rm H}(\boldsymbol{r}) = \frac{e^2}{\kappa}\int_{\mathbf{R}^2} d\boldsymbol{r}'\frac{\Delta n(\boldsymbol{r}')}{|\boldsymbol{r}-\boldsymbol{r}'|} \qquad H_0 = \frac{1}{2m^*}\boldsymbol{\pi}^2, \quad \text{with} \quad \boldsymbol{\pi} = \left(\boldsymbol{p} + \frac{e}{c}\boldsymbol{A}\right)$$

$$H_{\rm int} = \frac{1}{c}\int_{\mathbf{R}^2} d\boldsymbol{r}\,\boldsymbol{J}(\boldsymbol{r})\cdot\boldsymbol{A}_\gamma(\boldsymbol{r}) + \frac{e^2}{2m^*c}\int_{\mathbf{R}^2} d\boldsymbol{r}\,n_{\rm e}(\boldsymbol{r})A_\gamma^2(\boldsymbol{r}) \qquad \boldsymbol{A}_\gamma = \boldsymbol{e}_\phi \mathcal{A}_\gamma(a_\gamma^\dagger + a_\gamma)\left(\frac{r}{l}\right)$$

Long wavelength approximation

$$H_{\rm ext}(t) = F(t)\Big[g_\gamma\hbar\omega_c\{lI_x + lI_y\}(a_\gamma^\dagger + a_\gamma) + g_\gamma^2\hbar\omega_c\mathcal{N} \times \left\{\left(a_\gamma^\dagger a_\gamma + \frac{1}{2}\right) + \frac{1}{2}(a_\gamma^\dagger a_\gamma^\dagger + a_\gamma a_\gamma)\right\}\Big] \qquad g_\gamma = \left\{\left(\frac{e\mathcal{A}_\gamma}{c}\right)\frac{l}{\hbar}\right\}$$

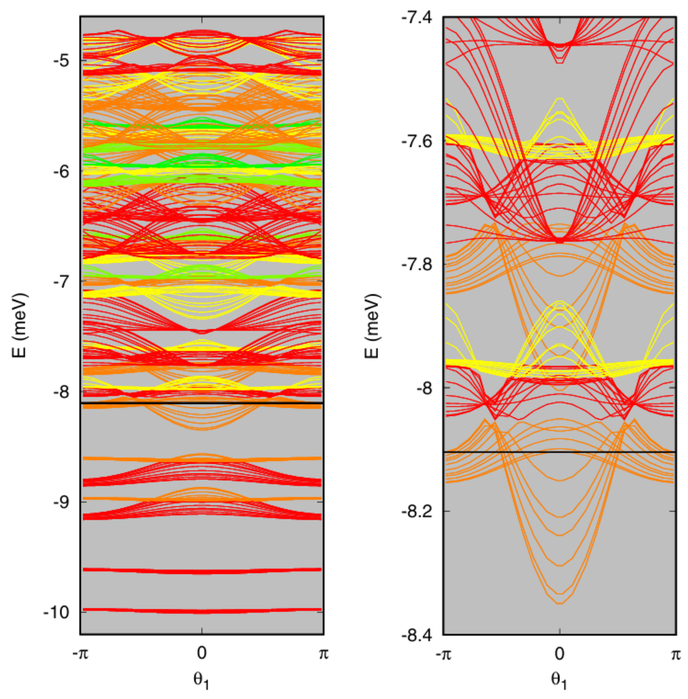
$$F(t) = \left(\frac{V_t}{\hbar\omega_c}\right)(\Gamma t)^2\exp(-\Gamma t)\cos(\omega_{\rm ext}t)$$

$$i\hbar\partial_t\rho^{\boldsymbol{\theta}}(t) = [H[\rho^{\boldsymbol{\theta}}(t)],\rho^{\boldsymbol{\theta}}(t)]$$ Liouville-von Neumann equation

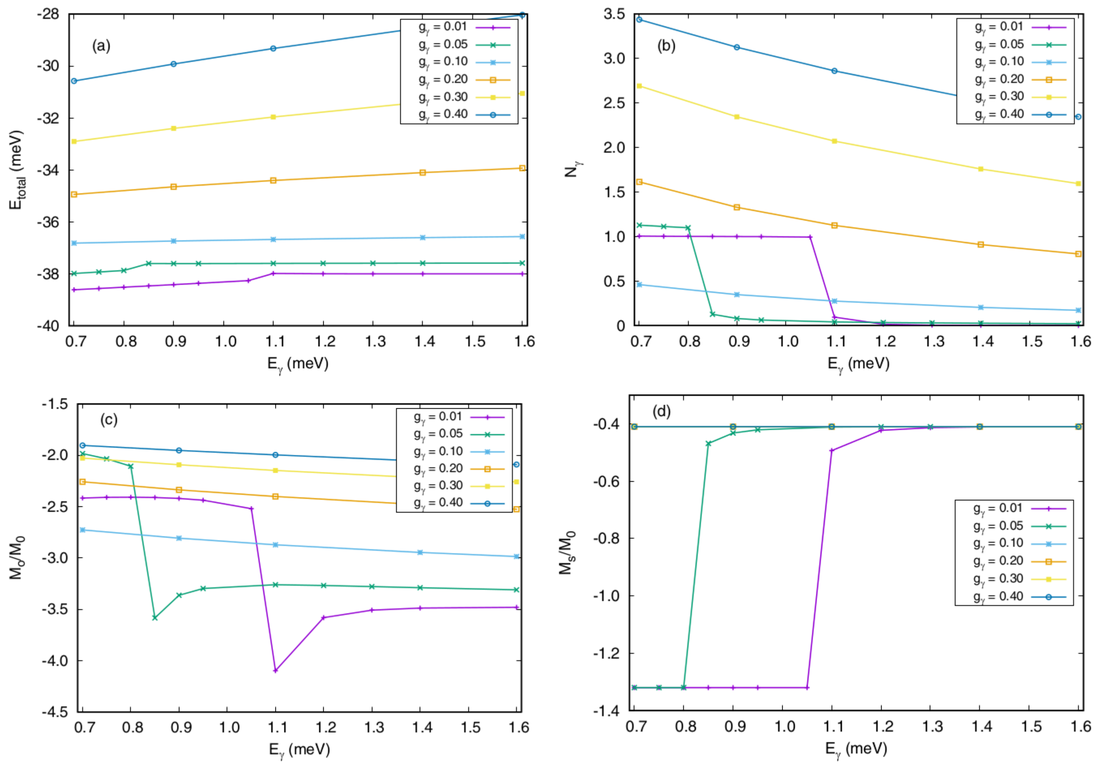
CONCLUSIONS

- We use QED-DFT-TP formalism to describe the e-e interaction and a configuration interaction approach for e-ph interaction for a 2DEG in a SL of QDs and QRs embedded in a cylindrical FIR-photon cavity in an external magnetic field.
- In the QR SL the Exchange Interaction is stronger than in the QD SL. For two electrons in each QR we observe a spin triplet state, even at low magnetic field.
- For three electrons in each QR we find a fully spin polarized state for low e-ph coupling and small photon energy. As the e-ph coupling or the photon energy are increased ***a transition to a single unpaired spin*** is observed.
- The excitation of the 2DEG does not promote a change in the mean spin configuration. The mean spin in each ring fluctuates around its original value.
- For stronger e-ph coupling we encounter beating patterns which are caused by interference of the fundamental peak in the Fourier Power Spectrum and the shifted second harmonics.

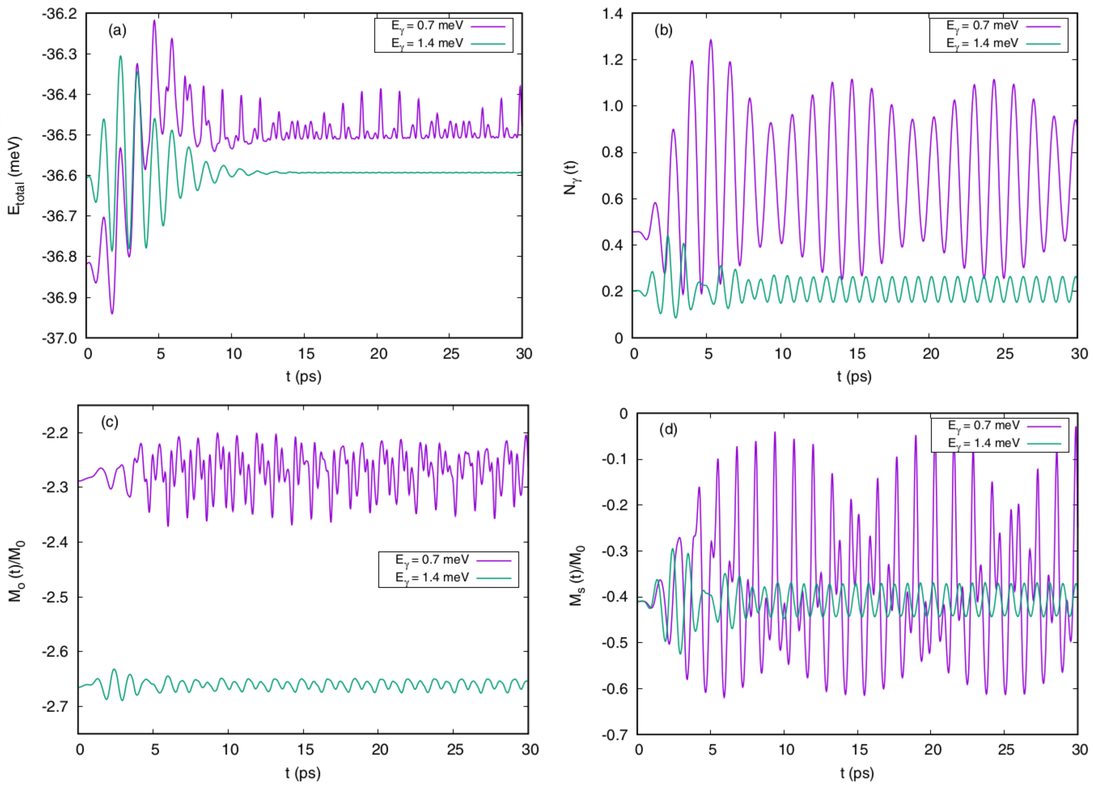
RESULTS



The energy band structure projected on one of the directions in the first Brillouin zone for Ne = 7, and pq = 2 (left) and a section of the same band structure in an energy range around the chemical potential (right). The color of the bands indicates their photon content with red for 0 and violet for 12.



(a) The total energy Etot, (b) the mean number of photons Nγ, (c) the orbital magnetization M0, and (d) the spin magnetization Ms of the 2DEG in a unit cell as functions of the photon energy Eγ for different values of the dimensionless electron-photon coupling. T = 1.0 K, Ne = 3, pq = 2, M0 = μ∗B /Auc.



(a) The total energy Etot, (b) the mean number of photons Nγ, (c) the orbital magnetization M0, and (d) the spin magnetization Ms of the 2DEG in a unit cell as functions of time for the first 30 ps for different values of the photon energy. gγ = 0.10, Ne = 3, pq = 2, and M0 = μ∗B /Auc.