

# Telecoms QD-molecules as multi-dimensional spin-photon interfaces

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Measurement based approaches to photonic quantum technologies rely on the upfront generation of multi-photon *cluster states* having 2D entanglement structures [1-3]. A deterministic protocol for generating such states using *always-on* exchange interaction between tunnel coupled spins in an optically active QD-molecule has recently been presented [3]. The coupled spins interact with two different photon frequencies in the two dots and entanglement is built up by free evolution of the spin-spin interaction combined with judiciously chosen optical driving. A prerequisite for realizing such sources is to deterministically prepare two spins and control and tune orbital couplings while optically driving the molecule for quantum light generation.

In this talk, I present recent efforts towards such deterministic sources of 2D-photonic cluster states using self-assembled InGaAs QD-molecules on GaAs substrates emitting both in near infrared (~930nm) and telecoms O-Band (1.3μm). Figure 1 shows a typical HAADF-STEM image of an O-Band molecule, showing the two dots (yellow) separated by an (Al)GaAs tunnel barrier. For O-band InAs/InGaAs QDMs, we observe electrically tunable quantum coupling via pronounced anticrossings between excitonic transitions, directly revealing kinetic exchange interaction and the hybridized states  $X^H$  arising from the coupling of the QD exciton

state with the quantum well states. We further optically map the interdot coupling strength as a function of interdot separation and demonstrate single-photon emission from an O-band QD-molecule with a  $g^{(2)}(0) = 0.017(2)$ . For near infra-red QDMs, results confirm that the tunnel coupling can be precisely engineered by epitaxial design, that single molecules can be optically charged with one or two spins while simultaneously maintaining the ability to widely tune orbital couplings using static electric fields and optically drive the system for quantum light generation [4-6]. We optically prepare one- and two-spin states, initialize via optical pumping and explore phonon mediated orbital and spin relaxation dynamics as a function of the energy detuning and hybridization of orbital states. Pronounced resonances and antiresonances are observed in the phonon-mediated orbital relaxation rates, varying from  $\mu\text{s}^{-1}$  -  $\text{ns}^{-1}$  as the splitting of the orbital states is tuned [6]. For two-spin states, remarkably long single-triplet (S-T) relaxation times are observed, extending beyond  $\sim 100 \mu\text{s}$  with strong dependence on the relative energy of ground and excited two-spin states [7]. We investigate the properties of two tunnel-coupled spins with magnetic fields applied in different geometries and demonstrate how g-tensors can be tuned via orbital tunnel coupling. Qualitative agreement is observed between  $\mathbf{k} \cdot \mathbf{p}$  calculations of excitonic structure, g-factors and phonon-mediated orbital relaxation.

Our results represent a new approach to prepare multi-spin systems in optically active QD-molecules opening the way to use them as deterministic sources for photonic cluster states with the two-dimensional entanglement structures required for measurement based quantum technologies.

## References

- [1] R. Raussendorf and H. J. Briegel, Phys. Rev. Lett. 86, 5188 (2001).
- [2] N. H. Lindner and T. Rudolph, Phys. Rev. Lett. 103, 113602 (2009).
- [3] M. Gimeno-Segovia, T. Rudolph and S. E. Economou, Phys. Rev. Lett. **123**, 070501 (2019).
- [4] F. Bopp et al. Phys. Rev. B 107 (16), 165426, (2023).
- [5] M Lienhart et al. Phys. Rev. B 112 (23), 235305, (2025).
- [6] C. Thalacker et al. arXiv:2603.05610, (2026).

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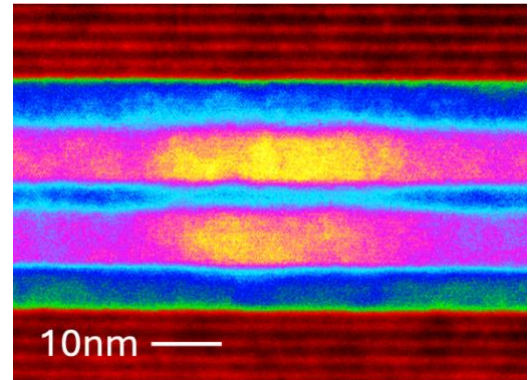


Figure 1 - False-color cross-sectional HAADF-STEM image of a single InAs/InGaAs QD-molecule.