S. A. Studenikin[1], A. Bogan[1], L. Gaudreau[1], M. Korkusinski[1], P. Zawadzki[1], L. A. Tracy[2], J. L. Reno[2], T. W. Hargett[2], and A. S. Sachrajda[1]

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Single and two hole spin qubits formed in a gated GaAs/AlGaAs double quantum dot

Motivation

The motivation for developing the hole spin-qubit platform is based on the attractive features of holes in a direct band gap semiconductor such as GaAs [1-3]:

- a predicted reduced hyperfine interaction between hole and nuclear spins
- a large spin-orbit interaction for fast spin qubit gate operations
- optically active transitions for developing hybrid spin-photon quantum devices
- a tuneable effective g-factor with field direction compatible with hybridization schemes between photons and spins.

[1] L. A. Tracy, et al., Appl. Phys.Lett. 104, 123101 (2014).
[2] A. Bogan, et al., Phys. Rev. Lett. 118, 167701 (2017).
[3] L. Gaudreau, et al., Semicond. Sci. Tech. 32, 093001 (2017).

The Double Quantum Dot Sample

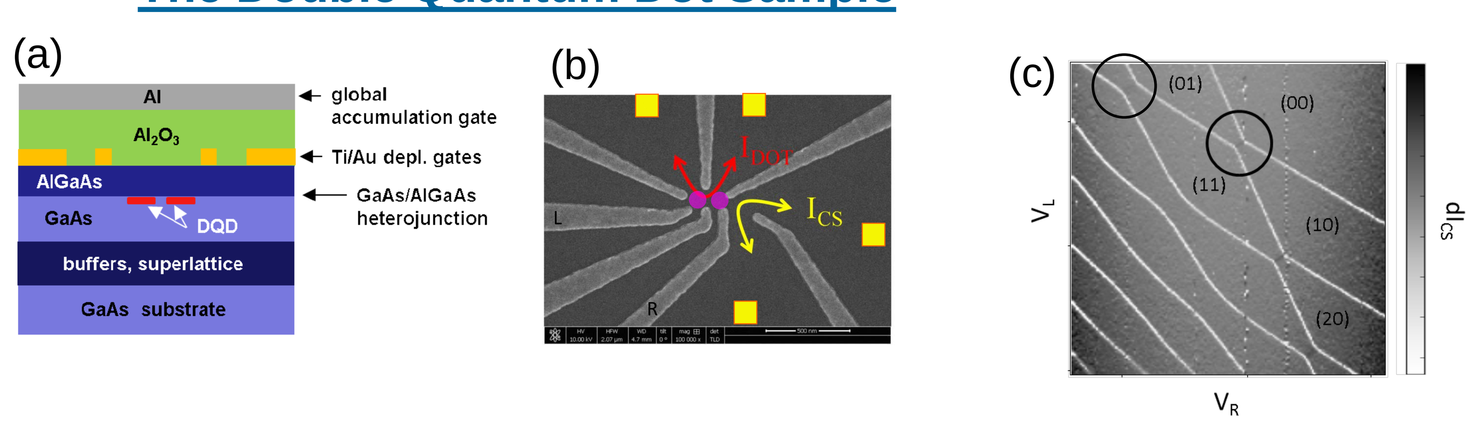

Figure 1.
(a) Cross section, (b) SEM image , and (c) charge stability diagram of the DQD device

Spin-flip t_F and spin-conserving t_N tunneling in single hole regime observed via transport measurements

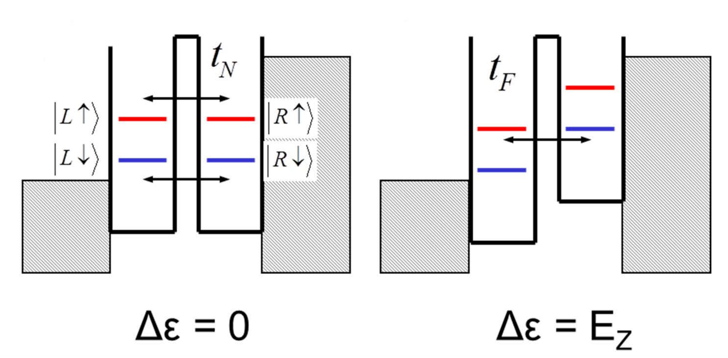

Figure 2.
(a) Energy level diagrams for zero detuning $\Delta\varepsilon=0$, t_N is spin-conserving tunnel coupling;
(b) same for $\Delta\varepsilon=E_z$ when transport occurs via spin-flip tunneling coupling t_F mediated by strong spin orbit coupling.

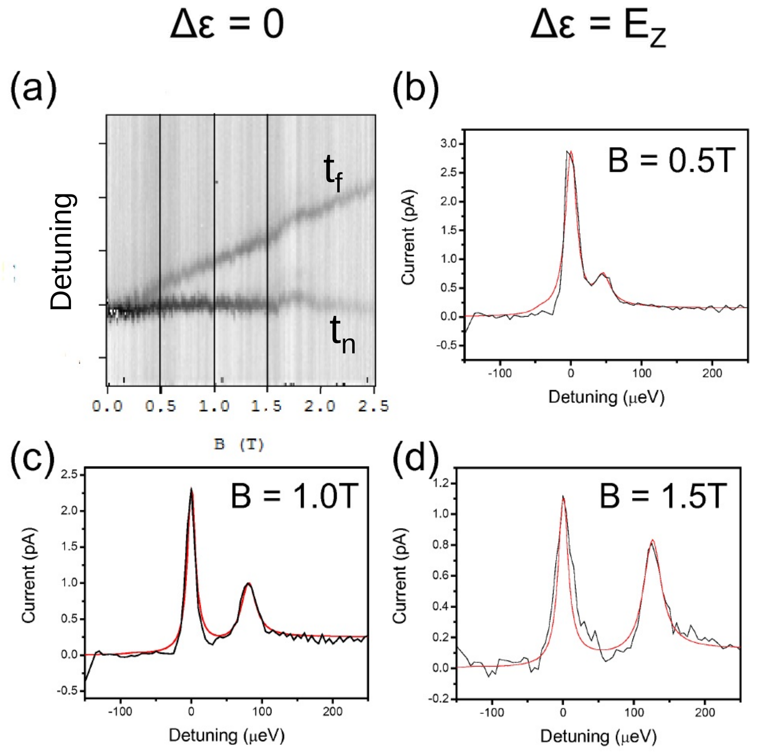

Figure 3.
(a) Magneto-transport tunnel current vs. detuning and magnetic field
(b-d) Examples tunneling current traces vs. detuning at different magnetic fields. The experimental traces are fitted by theory to extract t_N and t_F.

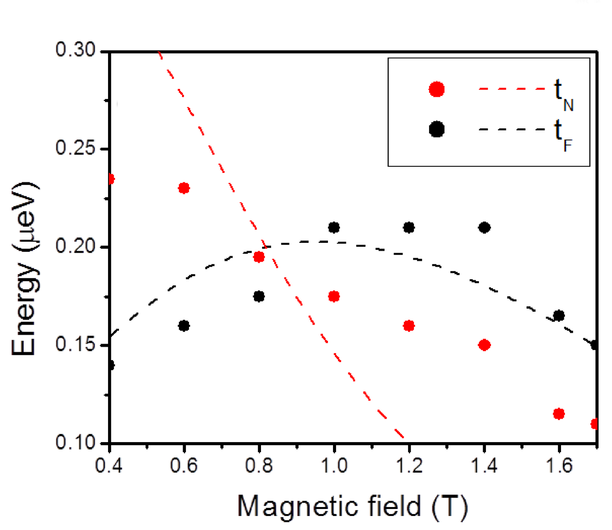

Figure 4.
Hole tunneling couplings extracted from the magneto-transport experiment above: spin-conserving (t_N) and spin-flip tunneling (t_F) couplings as a function of magnetic field. The spin flip tunneling coupling is several orders of magnitude larger than analogous values for electrons. [Fujita et al., Phys. Rev. Lett. 117, 206802 (2016)]

Single hole spin relaxation T1 in magnetic field

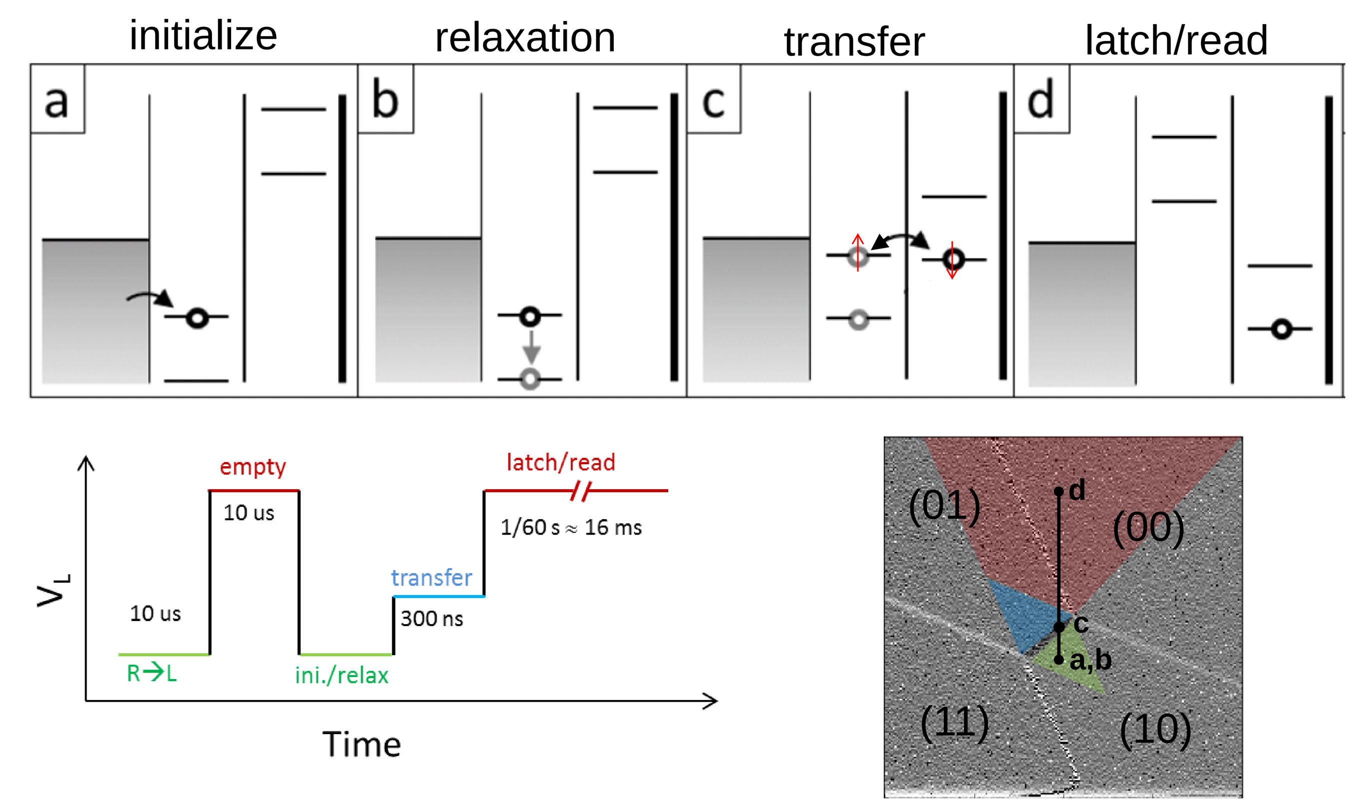

Figure 5. Level, pulse and stability diagrams illustrating the single-shot latching spin readout [S. A. Studenikin et al., Appl. Lett. 101, 33101 (2012)].

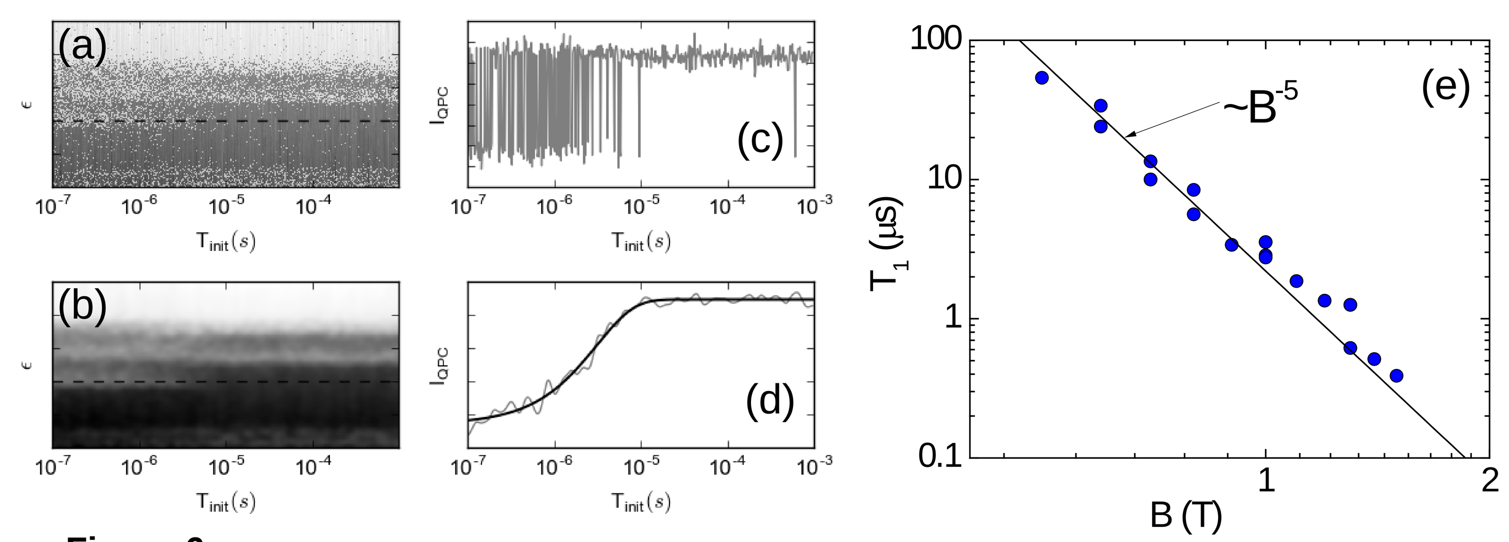

Figure 6.
Results of the single shot spin readout measurements. **(a)** raw data vs detuning ε and the relaxation time; **(b)** same plot as (a) but smoothed; **(c)** individual trace along the dash line in (a); **(d)** trace along the dash line in (b) fitted with an exponential dependence to determine T1; **(e)** single hole spin relaxation time T1 as a function of magnetic field.

LZS/PAT interferometry of a single hole charge and spin/charge hybrid qubits

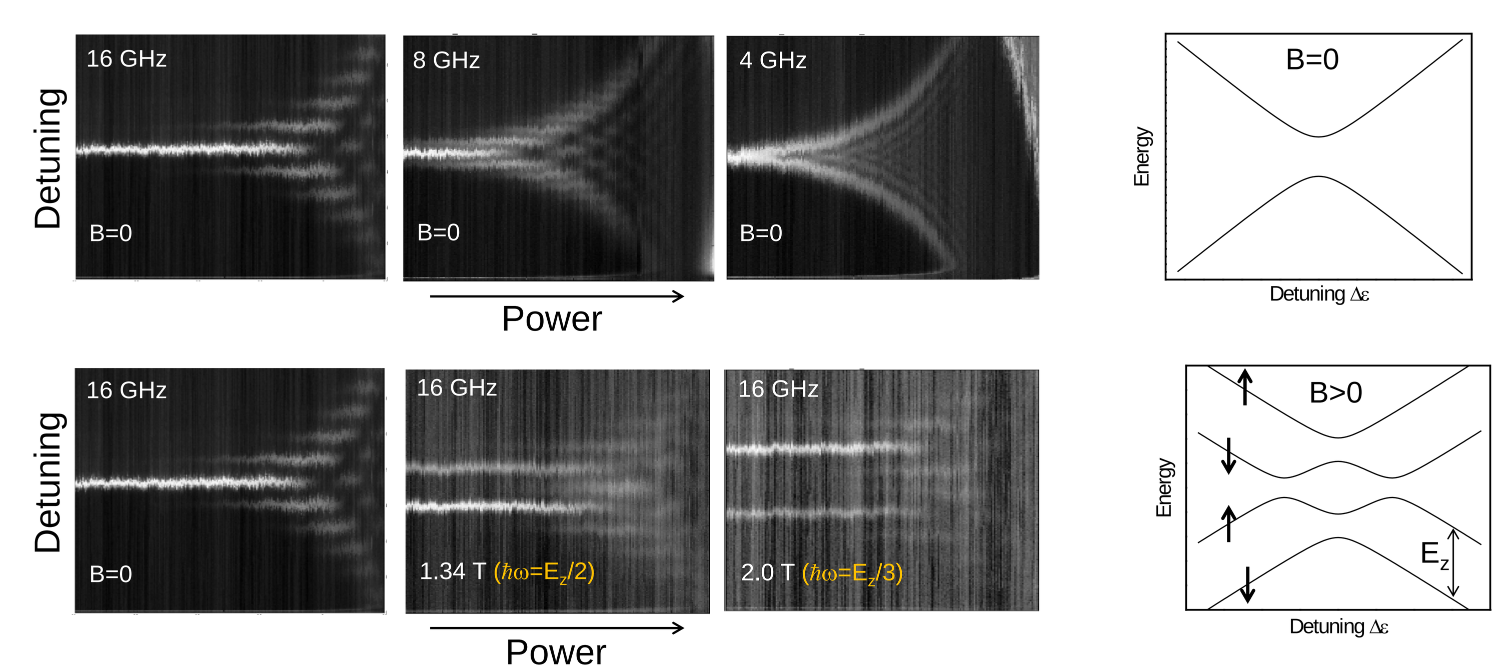

Figure 7. LZS/PAT patterns for different MW frequencies and magnetic fields, and energy diagrams for B=0 and B>0. The more complex behavior associated with both spin flip and spin conserving LZS can be seen.

LZS oscillations in a two-hole spin qubit

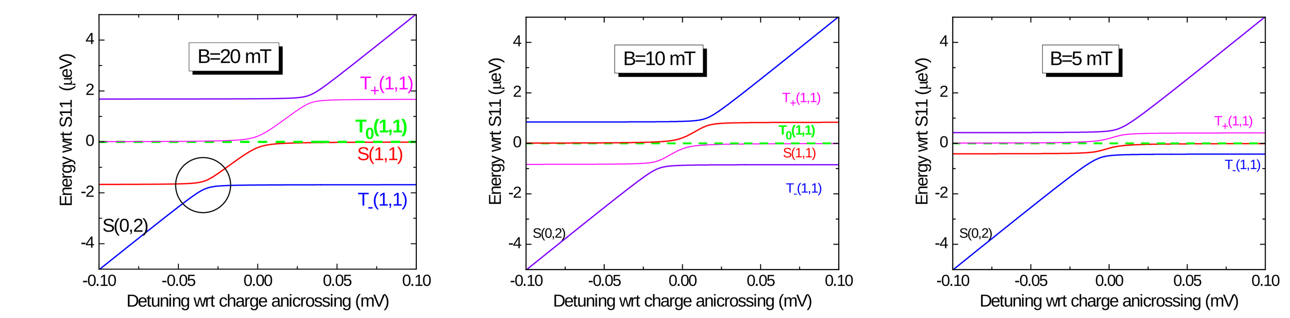

Figure 8. Energy spectra in the two-hole regime at different magnetic fields.

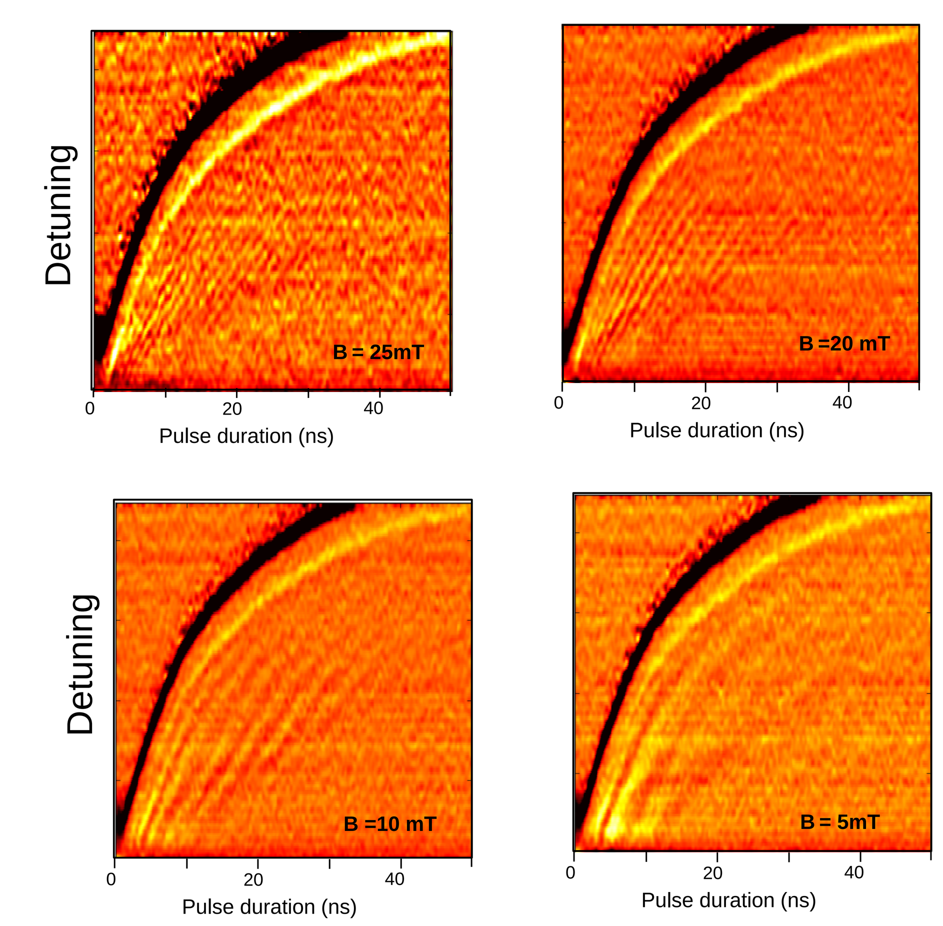

Figure 9.
Experimental LZS results at different magnetic fields using Gaussian convoluted pulse (10%-90% rise time τ≈10 ns).

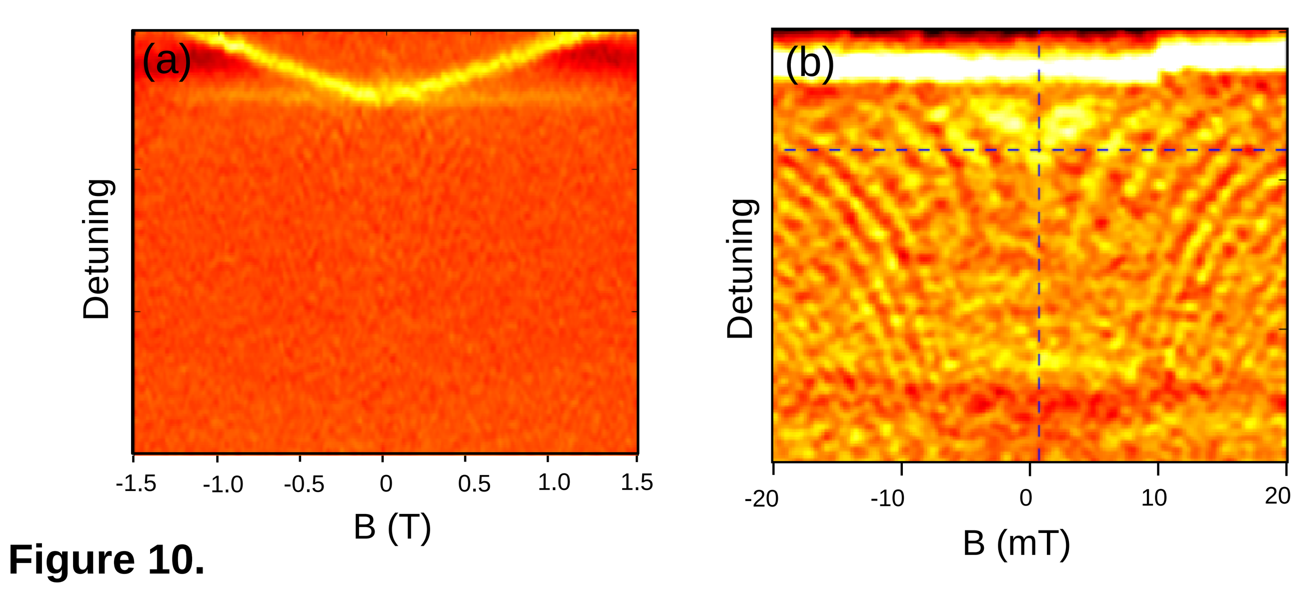

Figure 10.
(a) “Spin funnel” for the two-spin hole qubit over a large magnetic field range.
(b) LZS oscillations as a function of magnetic field (estimated coupling ~ 0.16 μeV)

Summary

A few hole spin system has been realized and studied in detail. Unlike the equivalent electron system, the behavior is dominated by the strong spin orbit interaction. In particular, here we showed:

- **Single and two hole coherent behaviour including hybrid spin-charge and singlet-triplet qubits**
- **The magnetic field dependence of the single hole relaxation time**

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