Experimental exploration of magnetic quantum phase transitions in germanium quantum dots

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Gate-defined semiconductor quantum dot arrays offer a promising platform for quantum simulation of a wide range of phenomena, with site-resolved electrical readout and control of both charge and spin states. Recent studies have demonstrated simulations of the Fermi-Hubbard model, Nagaoka ferromagnetism, Heisenberg spin chains, and exciton transport in a quantum dot array [1-4]. Building on these advances, we use a 2x4 germanium quantum dot ladder (see Figure 1) [5] to explore quantum phase transitions of triplons under a magnetic field [6].

In our experiment, we first form weakly coupled spin dimers along the rungs of the ladder. As intra-dimer exchange couplings are reduced, which is analogous to increasing the external magnetic field, we observe an increase in spin-triplet (triplon) populations. In Figure 2, a corresponding rise in average magnetization and a peak in magnetization variance indicate the onset of a phase transition. Also, the site-resolved readout of dimer states allows us to track the sequential population of triplons during the phase transition—an observation not possible in bulk materials. In the thermodynamic limit, this would correspond to transitions from a quantum disordered state (gapped singlets) to a polarized state (gapped triplets) via a gapless canted antiferromagnet state, which forms a BEC of triplons at low temperature. Furthermore, as shown in Figure 3, by enhancing the exchange couplings along one leg of the ladder, we observe a splitting of the magnetization variance peak—an effect that remains under investigation.

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[2] J.P. Dehollain, et al. Nature 579, 528–533 (2020)
[3] C.J. van Diepen, et al. Phys. Rev. X. 11, 041025 (2021)
[4] T.-K. Hsiao, et al. Phys. Rev. X. 14, 011048 (2024)
[5] X. Zhang, et al. Nat. Nanotechnol. 20, 209–215 (2025)
[6] T. Giamarchi, et al. Nat. Phys. 4, 198–204 (2008)

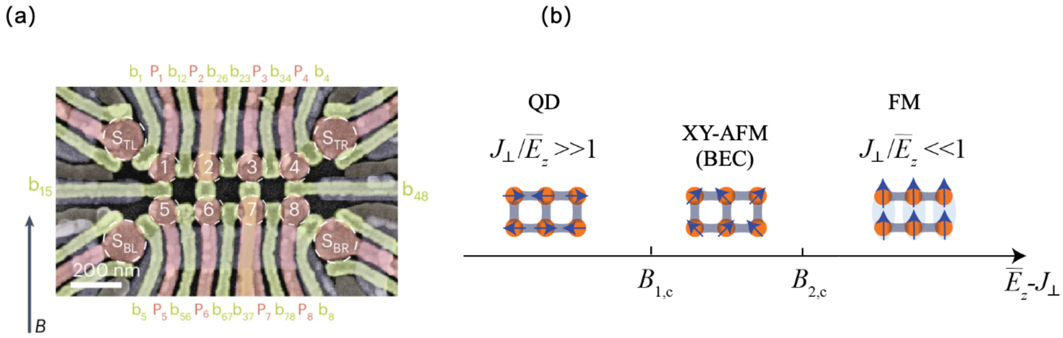

Figure 1: (a) False-coloured scanning electron microscope image of the germanium quantum dot device. The eight quantum dots are labelled 1–8, and four charge sensors are labelled S_{TL}, S_{TR}, S_{BL} and S_{BR}. A single hole spin is confined in each quantum dot. With strong vertical exchange couplings, an array of spin dimers is formed. (b) Phase diagram of Bose-Einstein condensation (BEC) in a dimerized quantum magnet as a function of E_z-$J_\perp$, where E_z is the average Zeeman energy induced by the applied magnetic field and $J_\perp$ is the intra-dimer exchange coupling. The phases involved include quantum disordered (QD) and field-aligned ferromagnetic (FM) phases and canted-antiferromagnetic (XY-AFM) phase where BEC occurs at low temperature. The cartoons represent the spin alignment of a quantum dot ladder in different phases.

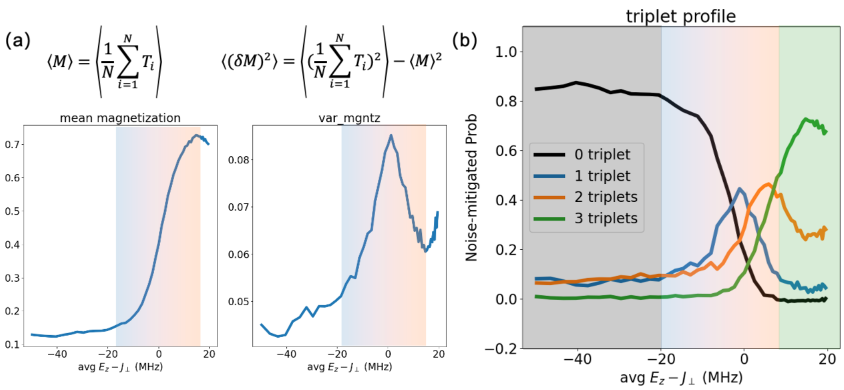

Figure 2: (a) Average magnetization and its variance as a function of the average vertical energy gap E_z-$J_\perp$ in a 2x3 quantum dot ladder. (b) Measured probabilities (corrected for readout errors) for having 0, 1, 2, and 3 triplet states along the rungs of a 2x3 quantum dot ladder as a function of the average vertical energy gap E_z-$J_\perp$. From left to right, the system's ground state transitions from a state formed by rung singlets (quantum disordered state, QD) to a canted antiferromagnet state (XY-AFM) and finally to a polarized state (field-aligned ferromagnet state, FM).

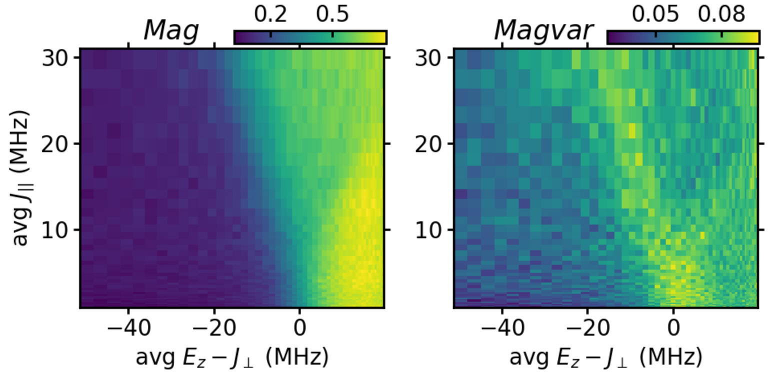

Figure 3: Average magnetization (left) and its variance (right) as a function of the average vertical energy gap E_z-$J_\perp$ and average horizontal exchange coupling of one leg ($J_{||}$) in a 2x3 quantum dot ladder. As $J_{||}$ increases, a plateau in the magnetization appears in the middle, whereas the single peak in variance develops into two peaks.