Optical Pumping of Electron Spins in Quantum Dot Ensembles

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Dortmund/St. Petersburg
Transregio 160 Dortmund/St Petersburg: Coherent manipulation of interacting spin excitations in tailored semiconductors
We verify that the quantum processor is working properly using a method called cross-entropy benchmarking [11,12,14], which compares how often each bitstring is observed experimentally with its corresponding ideal probability computed via simulation on a classical computer.
Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, [...] John M. Martinis

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Ein Quantum Überlegenheit?

Google verkündet die "Quantum Supremacy": Sein Sycamore-Chip soll dramatisch viel schneller rechnen als jeder Supercomputer bislang. IBM-Forscher zweifeln am Durchbruch.

Von Eike Kühl

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Fig. 1 The Sycamore processor. a, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. b, Photograph of the Sycamore chip.
Motivation

- works only at very low temperature (superconducting qubits)
- only nearest neighbor coupling of qubit
- IBM Q: results depend on the daily calibration
- quantum mechanical simulations on classical computers are still needed
Motivation

TRR 160: Coherent manipulation of interacting spin excitations in tailored semiconductors

- application of spin excitation for future technology
- exploitation of spin coherence: reducing power consumption of charge driven electronics
- potential embedding in traditional semiconductor structures
- manipulation with light: opto-spintronic integration
Optical pumping of electron spins in Quantum dot ensemble

1. Periodic pumping of quantum dot ensembles

2. Multi-color pumping: addressing different QDs

3. Higher-order spin noise: information on the coupling to the environment

\[ \vec{B} = B\vec{e}_x \]
Optical pumping of electron spins in Quantum dot ensemble

1. Periodic pumping of quantum dot ensembles

\[
\frac{d}{dt} \vec{S}(t) = \left( \vec{B}_N + \vec{B}_{\text{ext}} \right) \times \vec{S}(t) + \gamma P_{T\mu}(0) \vec{e}_z e^{-2\gamma t}
\]

- Larmor precession around an effective magnetic field: coherence
- coupling to nuclear spins: decoherence
- challenge: combine light-matter interaction and electron-nuclear spin dynamics
Revival of the spin polarization

Electron spin synchronization

Nuclear spin bath synchronization

decoherence: $T^*$
Revival of the spin polarization

Nuclear magnetic field $B_N$ distribution

\[ p(b_{N,x}) \sim \mathcal{N}(0, 1/3) \]

Resonance conditions

\[ \omega_L T_R = 2\pi n \]
\[ \omega_L T_R = \arctan(\omega_L / \gamma) + 2\pi n \]

Jäschke, PRB 2017
Analysis of the revival amplitude

revival amplitude: magnetic field dependent

• can we understand the non-linear dependency of the revival amplitude
• what is the role of the nuclear spins?

Kleinjohann et al, PRB, Oct 2018
Analysis of the revival amplitude

quantum mechanical simulation of 20mil pulses

• minimum: nuclear spin resonance condition
• experiment: different isotope mixtures

ωNT_R = πn

Kleinjohann et al, PRB, Oct 2018
Multi-color pumping: addressing different QDs

- Two color pumping of quantum dot ensembles

\[ J_{ij} \vec{S}_i \cdot \vec{S}_j \]

- Experimental data is consistent with an effective Heisenberg coupling between two quantum dots
- RKKY via wetting layer?
Multi-color pumping: addressing different QDs

\[ \frac{d}{dt} \vec{S}_i(t) = \left( \vec{B}_N^i + \vec{B}_{QDs}^{no-pump} + \vec{B}_{QDs}^{pumped} + \vec{B}_{ext} \right) \times \vec{S}_i(t) + \gamma P_{T\mu}^i(0) \vec{e}_z e^{-2\gamma t} \]

- two random Gaussian magnetic fields: the Overhauser field \( B_N \) and \( B_{QDs}^{no-pumped} \)
- coupled semiclassical differential equations plus QM light-matter interaction: massive parallelized on JURECA booster Intel Phi architecture

Fischer et al, PRB, Nov 2018
Multi-color pumping: addressing different QDs

- Resonance energy depends on the random shape of the QD
  - Sharp laser frequency: pumping of only one sub-ensemble

- Finite pulse:
  - Finite width $\Delta E$
  - Pumping several sub-ensembles
  - Synchronisation vs dephasing of unpumped QDs

$$\mathbf{B} = B\mathbf{e}_x$$

Decay time: $T^*$
Multi-color pumping: addressing different QDs

- Resonance energy depends on the random shape of the QD.
  - Sharp laser frequency: pumping of only one sub-ensemble.

- Finite pulse:
  - Finite width $\Delta E$
  - Pumping several sub-ensembles
  - Synchronisation vs dephasing of unpumped QDs

\[
\vec{B} = B\vec{e}_x
\]

\[Fischer\ et\ al,\ PRB,\ Nov\ 2018\]

JURECA BOOSTER: Intel Phi
Multi-color pumping: addressing different QDs

Summary of the multi-color pumping

• surprising experimental finding: decoherence time independent of the LASER energy width $\Delta E$
• simulation: consistent with spin-coupled QD spins

Questions

• origin of the coupling?
• can we learn to manipulate this coupling?
• coupling of different subset: qubit interactions?
• different pulse sequences

Fischer et al, PRB, Nov 2018
Higher-order spin noise in QDs

Spin noise

\[ C_2(t) = \text{Tr} [\rho S_z(t)S_z] \]

• spin noise: Fourier transformation of \( C_2(t) \)

\[ S(\omega) = C_2(\omega) = \langle |S_z(\omega)|^2 \rangle \]

Hackmann et al, PRL, 2015
Higher-order spin noise in QDs

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• message: \( C_2(t) \) is well understood

Higher order spin correlations

\[ C_4(t_1, t_2, t_3) = \langle S_z(t_1) S_z(t_2) S_z(t_3) S_z \rangle \]

1. spin echo \( C_4(t_1, t_1 + t_2, t_1) \)

2. 4th-order spin noise

\[ C_4(\omega_1, \omega_2) = \langle |S_z(\omega_1)|^2 |S_z(\omega_2)|^2 \rangle = \text{FT} \left[ \lim_{T_m \to \infty} \frac{1}{T_m} \int_{-T_m}^{T_m} d\tau C_4(t_1 + \tau, \tau, t_2) \right] \]

Fröhling, FBA, PRB 2017
Higher-order spin noise in QDs

4th-order spin noise

\[ S_4(\omega_1, \omega_2) = C_4(\omega_1, \omega_2) - C_2(\omega_1)C_2(\omega_2) \]

- crossover from a single spin to a classic continuum
- 4th-order: only correlation on the diagonal for a simple model
- finite magnetic field: Gaussian anti-correlations

Fröhling, Jäschke, FBA, PRB 2019
JUWELS simulations
Higher-order spin noise in QDs

4th-order spin noise: include quadrupolar interactions

$$S_4(\omega_1, \omega_2) = C_4(\omega_1, \omega_2) - C_2(\omega_1)C_2(\omega_2)$$

- off-diagonal noise: probe for additional interactions that causes decoherence
- modification of the Gaussian noise

Fröhling, Jäschke, FBA, PRB 2019
JUWELS simulations
Higher-order spin noise in QDs

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Fröhling, Jäschke, FBA, PRB 2019

JUWELS simulations
Summary

1. Numerical simulation of periodically pulsed quantum dot ensembles: understanding the synchronisation of the nuclear spin bath
2. Long-range spin interaction between quantum dots: coupling of subsystems pulsed with different laser colors
3. Proposal: higher-order spin correlation functions can reveal additional weak interactions

Thank you very much!