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7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

State University of New York (SUNY) at Bu
The UB Commons
520 Lee Entrance, Suite 211
Amherst, NY 14228 -2567

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RPPR Final Report
as of 28-Oct-2018

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Proposal Number: 62304PHQC **Agreement Number: W911NF-12-1-0609**

INVESTIGATOR(S):

Name: Xuedong Hu
Email: xhu@buffalo.edu
Phone Number: 7166455444
Principal: Y

Organization: **State University of New York (SUNY) at Buffalo**
Address: The UB Commons, Amherst, NY 142282567
Country: USA
DUNS Number: 038633251 EIN: 141368361

Report Date: 30-Jun-2017 Date Received: 22-Oct-2018
Final Report for Period Beginning 01-Oct-2012 and Ending 31-Mar-2017
Title: Theoretical Study of Solid State Quantum Information Processing
Begin Performance Period: 01-Oct-2012 **End Performance Period:** 31-Mar-2017
Report Term: 0-Other

Submitted By: Xuedong Hu Email: xhu@buffalo.edu
Phone: (716) 645-5444

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STEM Degrees: 1 **STEM Participants:** 0

Major Goals: The objective of this research program is to provide theoretical support to the study of solid state quantum computing. During the four years of this program, we have worked on two main aspects of spin qubits: decoherence, and coupling.

The major front of our research is on spin qubit decoherence, and we have mostly focused on decoherence of multiple qubits or non-equilibrium spin qubits. Specifically, we have completed our studies of two- and three-spin decoherence due to hyperfine interaction. We have investigated spin relaxation due to charge noise and/or spin-valley mixing, and found that charge noise and spin-valley mixing could both be an important ingredient to spin relaxation at relatively low magnetic fields. We have studied decoherence of a driven qubit, and found that the electron relaxation and dephasing properties are strongly modified by the presence of driving. We have studied the scaling behavior of decoherence for a multiple-spin-qubit system under the influence of hyperfine interaction, and found that the multi-qubit decoherence properties are reasonably favorable. Lastly, we have investigated relaxation of a moving spin qubit, and found that phonon bottleneck effect reduces spin relaxation for larger magnetic fields, and fast motion can reduce spin relaxation for a wide range of magnetic fields. We have studied dynamics and relaxation of the spin of a tunneling electron, and found regimes where spin relaxation is minimized and spin hot spot is eliminated.

Another front of our research is on coupling of spin qubits. We have studied effective coupling of two 31P nuclear spins mediated by the two confined donor electron spins that are exchange-coupled. We found that the coupling between the two dressed nuclear spins takes on an XY form, instead of the Heisenberg or XXZ form discussed before. We have studied exchange coupling of two singlet-triplet qubits, showing that the effective qubit coupling is of the Ising type. We have been building numerical tools to calculate 31P electron wave functions in Si from single to multiple donors in order to understand their couplings. We have also worked on electronic structure calculations for multi-electron-multiple-dots in both GaAs and Si substrates.

Accomplishments: Over the four and a half years from 2012 to 2016, we have completed the following tasks.

One theme of our research is to explore the effect of nuclear spins on an electron spin qubit, whether it is made of a single spin or multiple spins.

We have calculated decoherence of two- and three-electron spin states induced by hyperfine interaction with nuclear spins in the presence of a magnetic field gradient. We find that at the large magnetic field gradient limit (compared to the exchange interaction), two-spin decoherence approaches the single-spin limit. We have also calculated error rate of an exchange gate for two single-spin qubits due to random nuclear fields. A manuscript on this work is published in Physical Review B. For three-spin states, we have identified the most important leakage channels, and clarified the operating condition for a three-spin qubit. We find that both the inhomogeneous broadening and the pure dephasing rates for such a logical qubit are close to those for a single confined spin, and the decoherence properties are not significantly influenced by variations in the interdot exchange coupling. This work is published in Physical Review B.

We have analyzed statistically the scaling behavior of nuclear spin induced dephasing on uncoupled electron spin qubits. We find that the fidelity of a multi-qubit superposed state varies from no decay to a decay rate proportional to their polarization, to decay rates proportional to the square root of the number of qubits. Overall this is a quite favorable scaling behavior for the electron spin qubits. This work is published in Scientific Reports.

A second theme of our research is to study electron spin decoherence due to electrical noise (such as charge noise and electron-phonon interaction) and spin-orbit coupling, especially when the electron is driven out of equilibrium.

We have investigated decoherence of a confined electron spin due to charge noise and spin-orbit interaction. While spin-orbit interaction together with electron-phonon interaction is the main relaxation mechanism for electron spins at higher magnetic fields, we find that for lower external field charge noise could be an important, possibly dominant, contributor. This work is published in Physical Review B. We have applied our understanding of charge noise in the specific case of Si quantum dot that has spin-valley mixing. By including charge noise, particularly Johnson noise from the circuit, we can better describe the experimental results for lower magnetic fields (when Zeeman energy is lower than the valley splitting in the dot). This work is published in Physical Review B.

We have studied how a driving field alters the decoherence properties of a qubit. We find that driving changes the environment that the qubit experiences, thus can strongly affect decoherence of the qubit. In the case of an electrically driven spin qubit interacting with the phonon reservoir, we find that relaxation is reduced when the driving field is negatively detuned, while pure dephasing becomes possible and is maximized near resonance. This work is published in Physical Review A.

We have studied spin relaxation of a moving spin qubit through spin-orbit interaction and electron-phonon interaction. We find that Doppler effects lead to significant effects in fast moving quantum dots (QD). For example, the spin relaxation rate peaks when the QD motion is in the transonic regime, so that a moving spin qubit can have lower relaxation rate than a static qubit. In addition, the emitted phonons become strongly directional and narrow in their frequency range as the qubit reaches the supersonic regime, similar to Cherenkov radiation. This work is published in Scientific Reports.

A third theme of our research centers on the feasibility of donor spin qubits in Si for large-scale quantum computing.

We have studied the feasibility of using the nuclei of two donors to enable a singlet-triplet donor electron spin qubit in Si:P. Within the lowest order approximation the two donor nuclei can indeed act as a field gradient to allow singlet-triplet transition. This is in contrast with the two-donor-one-electron case, where an electrically driven spin resonance cannot be achieved because the highly symmetric hyperfine interaction between the electron and the donor nuclear spin limits the electron spin dynamics.

We have examined in detail the effective coupling between two Phosphorus nuclear spins mediated by their two donor electrons in Si:P, with the electrons coupled through exchange interaction (This is the original Kane proposal). Using quasi-degenerate perturbation method, we have constructed the effective electron spin Hamiltonian, and found that the coupling takes the simple XY form, instead of the Heisenberg or XXZ form that was discussed before.

Currently we are revisiting the electronic states of single and coupled donor system, with particular interest in clarifying how excited orbital states may affect the exchange coupling for coupled donors.

We have been studying the coupled donor-dot system in Si, including calculating its coherence properties and exploring its capability for long-distance coupling. In particular, we have calculated charge qubit relaxation as a function of the applied electric field. By examining the energy spectrum as a function of the applied field, we identify the optimal detuning between the donor and the interface state, such that charge noise induced dephasing is minimized. We have also found the form of the qubit interaction Hamiltonian when the individual systems are at their optimal point for decoherence. This work is performed by my graduate student John Truong, and is being written up.

In addition to the themed works above, we have studied other spin properties relevant to quantum control. For example, we have explored the effect of non-adiabaticity on single-spin time evolution in a changing magnetic field. We find that non-adiabaticity leads to corrections to the geometric phase of the spin, and leads to completely different time-energy relation than the adiabatic limit. This work is published in Scientific Reports.

We have multiple collaborations with groups around the country and world. For example, in collaboration with the theory group at the University of Wisconsin, led by Mark Friesen and Susan Coppersmith, we have studied quantum gates and hybrid qubits; in collaboration with an experimental group at University of Science and Technology China, we have explored how to expand the idea of hybrid qubit and multiple electron encoding, which resulted in several publications; in collaboration with groups at Riken, Japan, we have studied hole spin resonance and multi-electron entanglement.

Training Opportunities: During this program one graduate student (Jo-Tzu Hung) obtained her PhD degree, and one postdoctoral researcher (Dr. Peihao Huang) completed his training. Three new graduate students and one postdoctoral researcher have joined the group during this period of time. They are Luke Pendo, Bilal Tariq, John Truong, and Xinyu Zhao. They have made contributions to the research effort in my group, and have attended conferences and program reviews to present their results.

Results Dissemination: Dissemination of our results is mostly through two channels: publications in refereed journals, and presentations at conferences and academic institutions. From end of 2012 to 2016, we published 17 papers, in journals such as Physical Review A, B, and Letters. During this period my group members and I have given 19 invited talks and 32 contributed talks at international conferences, and I have given 15 seminars in various universities and research labs.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Xuedong Hu
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Peihao Huang
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Xinyu Zhao
Person Months Worked: 12.00 **Funding Support:**

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Jo-Tzu Hung
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Luke Pendo
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: John Truong
Person Months Worked: 4.00 **Funding Support:**
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International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Bilal Tariq
Person Months Worked: 2.00 **Funding Support:**
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Journal: Physical Review B
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevB.86.205306
Volume: 86 Issue: 20 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Controllable exchange coupling between two singlet-triplet qubits
Authors:
Keywords: spin qubit, singlet-triplet qubit, exchange coupling, two-qubit operation, generalized Hubbard model
Abstract: We study controllable exchange coupling between two singlet-triplet qubits.We start from the original second quantized Hamiltonian of a quadruple quantum dot system and obtain the effective spin-spin interaction between the two qubits using the projection operator method. Under a strong uniform external magnetic field and an inhomogeneous local micromagnetic field, the effective interqubit coupling is of the Ising type, and the coupling strength can be expressed in terms of quantum dot parameters. Finally, we discuss how to generate various two-qubit operations using this controllable coupling, such as entanglement generation, and a controlled-NOT gate.
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Article Title: Probing quantum phase transitions in a spin chain with a double quantum dot
Authors:
Keywords: spin chain, quantum phase transition, double dot, measurement
Abstract: Quantum phase transitions (QPTs) in qubit systems are known to produce singularities in the entanglement, which could in turn be used to probe the QPT. Recent proposals have suggested that the QPT in a spin chain could be probed via the entanglement between external qubits coupled to the spin chain. Such experiments may be technically challenging, because the probe qubits are nonlocal. Here we show that a double quantum dot coupled locally to a spin chain provides an alternative and efficient probe of a QPT. To demonstrate this method in a simple geometry, we propose an experiment to observe a QPT in a triple quantum dot, based on the well-known singlet projection technique.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
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Journal: Physical Review B
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevB.88.075301
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Date Submitted: Date Published:
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Article Title: Spin qubit relaxation in a moving quantum dot
Authors:
Keywords: spin qubit, spin relaxation, moving quantum dot, spin-orbit interaction, random potential
Abstract: Long-range quantum communication for spin qubits is an important open problem. Here we study decoherence of an electron spin qubit that is being transported in a moving quantum dot. We focus on spin decoherence due to spin-orbit interaction and a random electric potential. We find that at the lowest order, the motion induces longitudinal spin relaxation, with a rate linear in the dot velocity. Our calculated spin relaxation time ranges from sub ?s in GaAs to above ms in Si, making this relaxation a significant decoherence channel. Our results also give clear indications on how to reduce the decoherence effect of electron motion.
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Date Submitted: Date Published:
Publication Location:
Article Title: Hyperfine interaction induced dephasing of coupled spin qubits in semiconductor double quantum dots
Authors:
Keywords: two-spin decoherence, hyperfine interaction, double quantum dot
Abstract: We investigate theoretically the hyperfine-induced dephasing of two-electron-spin states in a double quantum dot with a finite singlet-triplet splitting J . In particular, we derive an effective pure dephasing Hamiltonian, which is valid when the hyperfine-induced mixing is suppressed due to the relatively large J and the external magnetic field.Using both a quantum theory based on resummation of ring diagrams and semiclassical methods,we identify the dominant dephasing processes in regimes defined by values of the external magnetic field, the singlet-triplet splitting, and inhomogeneity in the total effective magnetic field. We address both free induction and Hahn echo decay of superposition of singlet and unpolarized triplet states (both cases are relevant for singlet-triplet qubits realized in double quantum dots). We also study hyperfine-induced exchange gate errors for two single-spin qubits. Results for III-V semiconductors as well as silicon-based quantum dots are presented.
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Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.87.022332
Volume: 87 Issue: 2 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Resonant adiabatic passage with three qubits
Authors:
Keywords: adiabatic teleportation, adiabatic passage, resonant state transfer, three qubits
Abstract: We investigate the nonadiabatic implementation of an adiabatic quantum teleportation protocol, finding that perfect fidelity can be achieved through resonance. We clarify the physical mechanisms of teleportation, for three qubits, by mapping their dynamics onto two parallel and mutually coherent adiabatic passage channels. By transforming into the adiabatic frame, we explain the resonance by analogy with the magnetic resonance of a spin-1/2 particle. Our results establish a fast and robust method for transferring quantum states and suggest an alternative route toward high-precision quantum gates.
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Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.86.062328
Volume: 86 Issue: 6 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Mediated gates between spin qubits
Authors:
Keywords: mediated gates, spin qubits, spin bus
Abstract: In a typical quantum circuit, nonlocal quantum gates are applied to nonproximal qubits. If the underlying physical interactions are short-range (e.g., exchange interactions between spins), intermediate SWAP operations must be introduced, thus increasing the circuit depth. Here we develop a class of "mediated" gates for spin qubits, which act on nonproximal spins via intermediate ancilla qubits. At the end of the operation, the ancillae return to their initial states. We show how these mediated gates can be used (1) to generate arbitrary quantum states and (2) to construct arbitrary quantum gates. We provide some explicit examples of circuits that generate common states [e.g., Bell, Greenberger-Horne-Zeilinger (GHZ), W, and cluster states] and gates (e.g., ? SWAP, SWAP, CNOT, and Toffoli gates). We show that the depths of these circuits are often shorter than those of conventional SWAP-based circuits. We also provide an explicit experimental proposal for implementing a mediated gate in a
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Volume: 5 Issue: 1 First Page #:
Date Submitted: 8/29/18 12:00AM Date Published: 11/1/15 4:00AM
Publication Location:
Article Title: Scaling of decoherence for a system of uncoupled spin qubits
Authors: Jun Jing, Xuedong Hu
Keywords: scaling, decoherence, spin qubit
Abstract: We study decoherence of a multi-spin-qubit state under the influence of hyperfine interaction, and clearly demonstrate that the state structure is crucial to the scaling behavior of n-spin decoherence. Specifically, we find that coherence times of a multi-spin state at most scale with the number of qubits n as square root of n, while some states with higher symmetries have scale-free coherence with respect to n. Statistically, convergence to these scaling behavior is generally determined by the size of the Hilbert space m, which is usually much larger than n (up to an exponential function of n), so that convergence rate is very fast as we increase the number of qubits. Our results can be extended to other decoherence mechanisms, including in the presence of dynamical decoupling, which allow meaningful discussions on the scalability of spin-based quantum coherent technology.
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Acknowledged Federal Support: **Y**

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Volume: 95 Issue: 3 First Page #:
Date Submitted: 8/30/18 12:00AM Date Published: 1/1/17 12:00AM
Publication Location:
Article Title: Spin blockade and coherent dynamics of high-spin states in a three-electron double quantum dot
Authors: Bao-Bao Chen, Bao-Chuan Wang, Gang Cao, Hai-Ou Li, Ming Xiao, Guang-Can Guo, Hong-Wen Jiang
Keywords: spin blockade, double quantum dot, Landau-Zener-Stuckelburg interference
Abstract: Asymmetry in a three-electron double quantum dot (DQD) allows spin blockade, when spin-3/2 (quadruplet) states and spin-1/2 (doublet) states have different charge configurations. We have observed this DQD spin blockade near the (1,2)-(2,1) charge transition using a pulsed-gate technique and a charge sensor. We then use this spin blockade to detect Landau-Zener-Stuckelberg interference and coherent oscillations between the spin quadruplet and doublet states. Such studies add to our understandings of coherence and control properties of three-spin states in a double dot, which, in turn, would benefit explorations into various qubit encoding schemes in semiconductor nanostructures.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Contract number: W911NF-12-1-0609

Project title: Theoretical study of solid state quantum information processing

Principal Investigator: Xuedong Hu
Postdoctoral Associates: Peihao Huang, Xinyu Zhao
Graduate Students: Jo-Tzu Hung, Luke Pendo, John Truong, Bilal Tariq
Start Date: October 1, 2012
End Date: December 31, 2016

Main Project Goals:
The main goal of this project is to study decoherence and quantum control of multi-qubit states, particularly for spin qubits in semiconductors.

Project Description:

The objective of this research program is to provide theoretical support to the study of solid state quantum computing. During the four years of this program, we have worked on two main aspects of spin qubits: decoherence, and coupling.

The major front of our research is on spin qubit decoherence, and we have mostly focused on decoherence of multiple qubits or non-equilibrium spin qubits. Specifically, we have completed our studies of two- and three-spin decoherence due to hyperfine interaction. We have investigated spin relaxation due to charge noise and/or spin-valley mixing, and found that charge noise and spin-valley mixing could both be an important ingredient to spin relaxation at relatively low magnetic fields. We have studied decoherence of a driven qubit, and found that the electron relaxation and dephasing properties are strongly modified by the presence of driving. We have studied the scaling behavior of decoherence for a multiple-spin-qubit system under the influence of hyperfine interaction, and found that the multi-qubit decoherence properties are reasonably favorable. Lastly, we have investigated relaxation of a moving spin qubit, and found that phonon bottleneck effect reduces spin relaxation for larger magnetic fields, and fast motion can reduce spin relaxation for a wide range of magnetic fields. We have studied dynamics and relaxation of the spin of a tunneling electron, and found regimes where spin relaxation is minimized and spin hot spot is eliminated.

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Accomplishments over duration of the grant:

Over the four and a half years from 2012 to 2016, we have completed the following tasks.

One theme of our research is to explore the effect of nuclear spins on an electron spin qubit, whether it is made of a single spin or multiple spins.

We have calculated decoherence of two- and three-electron spin states induced by hyperfine interaction with nuclear spins in the presence of a magnetic field gradient. We find that at the large magnetic field gradient limit (compared to the exchange interaction), two-spin decoherence approaches the single-spin limit. We have also calculated error rate of an exchange gate for two single-spin qubits due to random nuclear fields. A manuscript on this work is published in Physical Review B. For three-spin states, we have identified the most important leakage channels, and clarified the operating condition for a three-spin qubit. We find that both the inhomogeneous broadening and the pure dephasing rates for such a logical qubit are close to those for a single confined spin, and the decoherence properties are not significantly influenced by variations in the interdot exchange coupling. This work is published in Physical Review B.

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Currently we are revisiting the electronic states of single and coupled donor system, with particular interest in clarifying how excited orbital states may affect the exchange coupling for coupled donors.

We have been studying the coupled donor-dot system in Si, including calculating its coherence properties and exploring its capability for long-distance coupling. In particular, we have calculated charge qubit relaxation as a function of the applied electric field. By examining the energy spectrum as a function of the applied field, we identify the optimal detuning between the donor and the interface state, such that charge noise induced dephasing is minimized. We have also found the form of the qubit interaction Hamiltonian when the individual systems are at their optimal point for decoherence. This work is performed by my graduate student John Truong, and is being written up.

In addition to the themed works above, we have studied other spin properties relevant to quantum control. For example, we have explored the effect of non-adiabaticity on single-spin time evolution in a changing magnetic field. We find that non-adiabaticity leads to corrections to the geometric phase of the spin, and leads to completely different time-energy relation than the adiabatic limit. This work is published in Scientific Reports.

We have multiple collaborations with groups around the country and world. For example, in collaboration with the theory group at the University of Wisconsin, led by Mark Friesen and Susan Coppersmith, we have studied quantum gates and hybrid qubits; in collaboration with an experimental group at University of Science and Technology China, we have explored how to expand the idea of hybrid qubit and multiple electron encoding, which resulted in several publications; in collaboration with groups at Riken, Japan, we have studied hole spin resonance and multi-electron entanglement.

Publications (2012 to 2016):

1. J. Fei, D. Zhou, Y.-P. Shim, S. Oh, X. Hu, and M. Friesen. Mediated gates between spin qubits, Physical Review A **86**, 062328 (2012);
2. R. Li, X. Hu, and J. Q. You, Controllable exchange coupling between two singlet-triplet qubits, Physical Review B **86**, 205306 (2012);
3. Y.-P. Shim, S. Oh, Jianjia Fei, X. Hu, and M. Friesen, Probing quantum phase transitions in a spin chain with a double quantum dot, Physical Review B **87**, 155405 (2013);
4. T. Tanamoto, Y.-X. Liu, X. Hu, and F. Nori, Detection of a charged two-level system by using the Kondo and the Fano-Kondo effects in quantum dots, Japanese Journal of Applied Physics **52**, UNSP 04CJ03 (2013).
5. P. Huang and X. Hu, Spin qubit relaxation in a moving quantum dot, Physical Review B **88**, 075301 (2013);
6. J. Hung, L. Cywinski, X. Hu, S. Das Sarma, Hyperfine interaction induced dephasing of coupled spin qubits in semiconductor double quantum dots, Physical Review B **88**, 085314 (2013);
7. S. Oh, Y.-P. Shim, J. Fei, M. Friesen, X. Hu, Resonant adiabatic passage with three qubits, Physical Review A **87**, 022332 (2013);
8. A. Khaetskii, V. N. Golovach, X. Hu, and I. Žutic, Proposal for a Phonon Laser Utilizing Quantum Dot Spin States, Physical Review Letters **111**, 186601 (2013);
9. J. Jing, P. Huang, and X. Hu, Decoherence of an electrically driven spin qubit, Physical Review A **90**, 022118 (2014);
10. P. Huang and X. Hu, Spin relaxation in a Si quantum dot due to spin-valley mixing, Physical Review B **90**, 235315 (2014);
11. P. Huang and X. Hu, Electron spin relaxation due to charge noise, Physical Review B **89**, 195302 (2014);
12. J.-T. Hung, J. Fei, M. Friesen, X. Hu, Decoherence of an exchange qubit by hyperfine interaction, Physical Review B **90**, 045308 (2014);
13. J.J. Fei, J.-T. Hung, T.S. Koh, Y.-P. Shim, S.N. Coppersmith, X. Hu, and M. Friesen, Characterizing gate operations near the sweet spot of an exchange-only qubit, Physical Review B **91**, 205434 (2015).
14. J. Jing and X. Hu, "Scaling of Decoherence for a Decoupled Multi-spin System", arXiv:1502.07815. Scientific Reports **5**, 17013 (2015).
15. S. Oh, X. Hu, F. Nori, S. Kais, "Singularity of the time-energy uncertainty in adiabatic perturbation and cycloids on a Bloch sphere", arXiv:1507.07082. Scientific Reports **6**, 20824 (2016).

16. X. Zhao, P. Huang, and X. Hu, “Doppler effect induced spin relaxation boom”, arXiv:1503.00014. Scientific Reports **6**, 23169 (2016).
17. G. Cao, H.-O. Li, G.-D. Yu, B.-C. Wang, B.-B. Chen, X.-X. Song, M. Xiao, G.-C. Guo, H.-W. Jiang, X. Hu, and G.-P. Guo, “A Tunable Hybrid Qubit in a GaAs Double Quantum Dot”, arXiv:1510.00895. Physical Review Letters **116**, 086801 (2016).

Invited Presentations and Seminars (2012 to 2016):

1. Colloquium, SUNY Brockport, Brockport, New York, November, 2012.
2. Colloquium, Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, Canada, December, 2012.
3. Invited talk, The 6th EMN conference, Houston, Texas, January, 2013.
4. One contributed talk, Si Qubit Workshop, Grenoble, France, February, 2013.
5. Seven contributed talks, The APS March Meeting, Baltimore, Maryland, March, 2013.
6. Invited talk, The International Workshop on Frontiers in Quantum Information Science, Shanghai, China, June, 2013.
7. Invited talk, 2013 CMOS Emerging Technologies Research Workshop, Whistler, British Columbia, Canada, July, 2013.
8. Invited talk, The International Conference on Applied Mathematics, Modeling and Computational Science (AMMCS 2013), Waterloo, Canada, August, 2013.
9. Invited talk, International Workshop on Solid State Quantum Computing, Beijing, China, October, 2013.
10. Invited talk, Physics at the Falls workshop series: Common challenges in finite fermion systems, Buffalo, New York, November, 2013.
11. Five contributed talks, The APS March Meeting, Denver, Colorado, March, 2014.
12. Seminar, University of Rochester, New York, February, 2014.
13. Seminar, Syracuse University, New York, April, 2014.
14. Seminar, Beijing Computational Research and Science Center, Beijing, China, July, 2014.
15. Seminar (given by J. Jing), The Program on Electron Spin Qubit, Kavli Institute of Theoretical Physics China, Beijing, China, July, 2014.
16. Invited talk, The 2nd School and Conference on Spin-Based Quantum Information Processing, Konstanz, Germany, August, 2014.
17. Invited talk, Advanced many-body and statistical methods in mesoscopic systems II (MESO2014), Brasov, Romania, September, 2014.
18. Invited talk (given by J. Hung), Physics at the Falls workshop series: the 4th International Workshop on Entanglement, Decoherence, and Quantum Control, Buffalo, New York, October, 2014.
19. Seminar, University of Maryland Baltimore County, October, 2014.
20. Invited talk, The 8th Asia-Pacific Conference and Workshop on Quantum Information Sciences, Tainan, Taiwan, December, 2014.
21. Three contributed talks, The APS March Meeting, San Antonio, Texas, March, 2015.
22. Invited talk, Quantum Computing and Communications, the 112th Topical Symposium of The New York Section of the American Physical Society, Fredonia, New York, April, 2015.

23. Seminar, University of Science and Technology China, Hefei, May, 2015.
24. Invited talk, The 7th International Workshop on Solid State Quantum Computing (IWSSQC7), Nanjing, China, July, 2015.
25. Seminar, Center for Emergent Matter Science, Riken, Japan, August, 2015.
26. Contributed talk, Silicon Nanoelectronics Workshop, Takamatsu, Japan, August, 2015.
27. Seminar, Department of Physics, Federal University of Rio De Janeiro, Brazil, November, 2015.
28. Contributed talk, The APS March Meeting, Baltimore, Maryland, March, 2016.
29. Seminar, Beijing Computational Science Research Center, June, 2016.
30. Contributed talk, "Decoherence of a moving spin qubit", the 33rd International Conference on the Physics of Semiconductors, Beijing, China, August, 2016.
31. Seminar, "Relaxation of a Moving Spin Qubit", School of Physics, University of New South Wales, Sydney, Australia, October, 2016.
32. Seminar, "Relaxation and coupling of charge and flip-flop qubits", Morello group, University of New South Wales, Sydney, Australia, October, 2016.
33. Invited talk, "Non-Adiabatic Manipulation of Spin States with Adiabatic Protocols", International Workshop on Spin Coherence and Topological Order in Semiconductor Nanosystems, Beijing, November, 2016.
34. Invited talk, "Explorations on a Si:P spin qubit coupled via charge motion", The 8th International Workshop on Solid State Quantum Computing (IWSSQC8), Taipei, Taiwan, December, 2016.

Figures

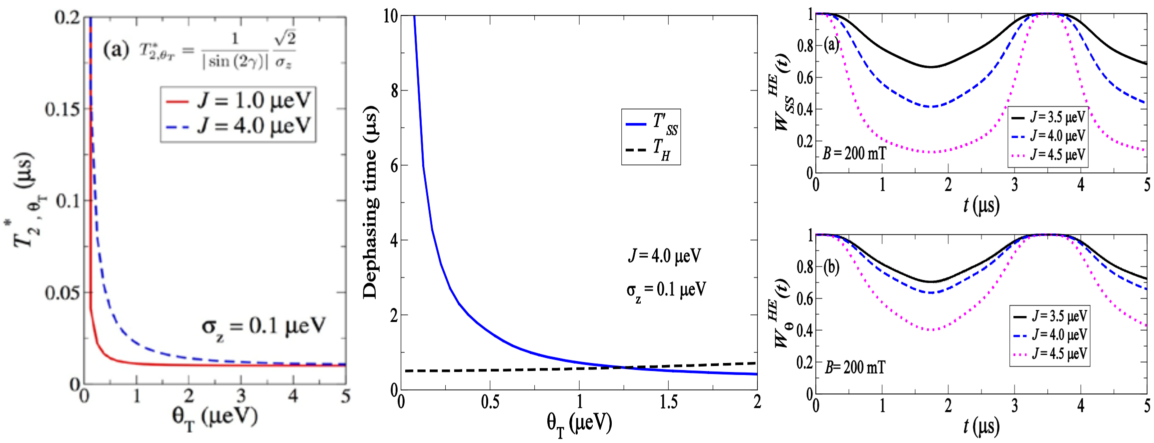

Fig. 1. Two-spin dephasing due to hyperfine interaction in the presence of a field gradient in a GaAs double dot. The left-most panel gives inhomogeneous broadening time due to random nuclear polarization. Clearly the dephasing time is severely suppressed by the field gradient. The middle panel shows the dephasing times of the dominant pure dephasing channels, with one insensitive to the field gradient, while the other going down quickly with the increasing gradient. The right panel shows Hahn echo decay of the two-spin coherence function. The qualitative behavior here is similar to that for a single spin in a single dot, with the modulation coming from interference between different nuclear spin species. The field gradient here is large, at 40 mT. For smaller gradients the signal modulation magnitude become smaller as well.

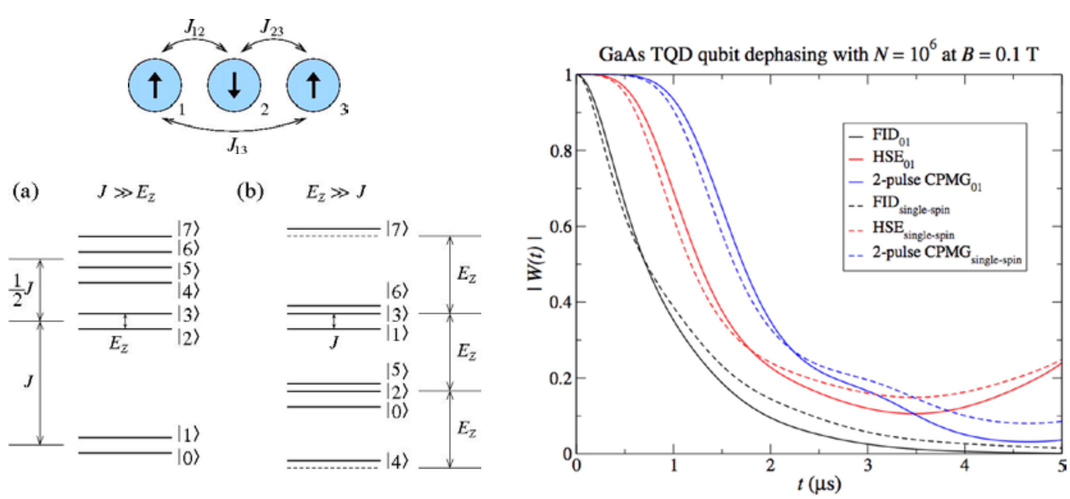

Fig. 2. Decoherence of three-spin states. On the top of the left panel is a schematic of the coupled triple dot. In our case we have taken $J_{12} = J_{23} = J$ and $J_{13} = 0$, so that we have a uniform linear chain. At the bottom of the left panel we give the spectrum of the three-spin system, at two useful limits. Panel (a) is the condition for a three-node spin bus, while panel (b) satisfies the conditions for the DiVincenzo encoding scheme, with states |0> and |2> encoding the logical qubit. On the right side we give the results of our pure dephasing calculation for the logical qubit, including those for free induction decay, Hahn echo decay, and 2-pulse CPMG echo decay. The dashed lines give the respective results for a single spin qubit in a single dot. Clearly, the three-spin logical qubit has very similar dephasing properties as a single-spin qubit.

Figures

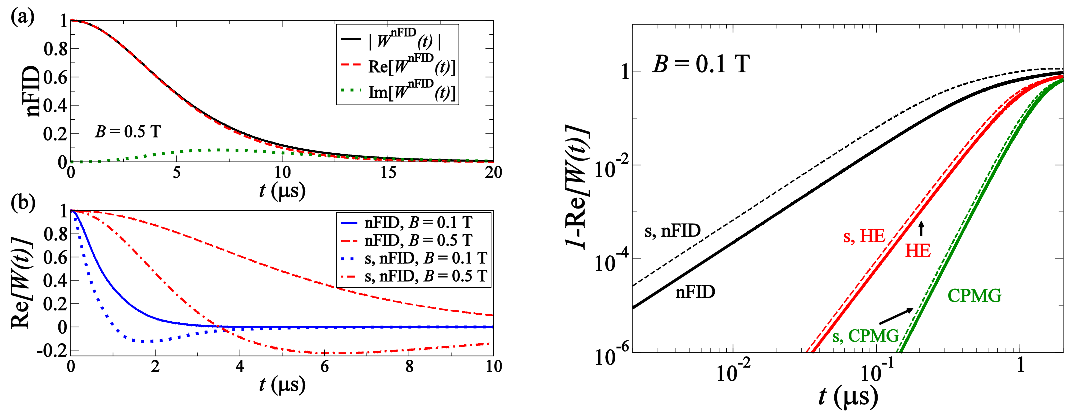

Fig. 3. Three-spin dephasing due to hyperfine interaction in a GaAs triple dot for an exchange-only qubit. The left figure shows the narrowed free induction decay (nFID) of an exchange-only qubit. The upper panel gives the real and imaginary parts and the absolute value of the coherence function for the qubit. The lower panel gives the nFID at different fields of 0.1 and 0.5 T, with benchmark values of single-spin FID (s, nFID). This figure shows that the nFID for the exchange only qubit is slightly slower than that for a single-spin qubit. The right figure gives the results of Hahn echo decay and CPMG echo decay, with their initial decay having a t^4 and t^6 dependence, as compared to the t^2 dependence of the nFID. Clearly, the echo decay is much slower than the nFID.

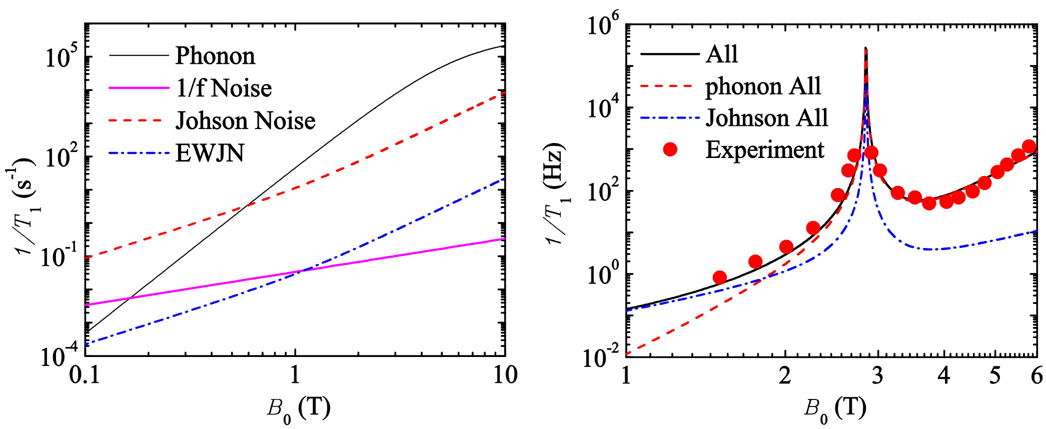

Fig. 4. Spin relaxation due to charge noise and spin-orbit interaction. The left pane shows the results for an electron confined in a GaAs quantum dot. At higher fields (above 1 T) phonon noise is the main relaxation channel, while for lower fields Johnson noise is the main channel. The right panel shows the results for an electron confined in a Si quantum dot. The sharp peak slightly below 3 T is due to spin-valley mixing in the Si dot, when the Zeeman energy is on resonance with the valley splitting of the two-dimensional dot. The red dots are experimental results from Dzurak group. We can see that only by including both phonon and Johnson noise can we properly fit the experimental results with reasonable system parameters.

Figures

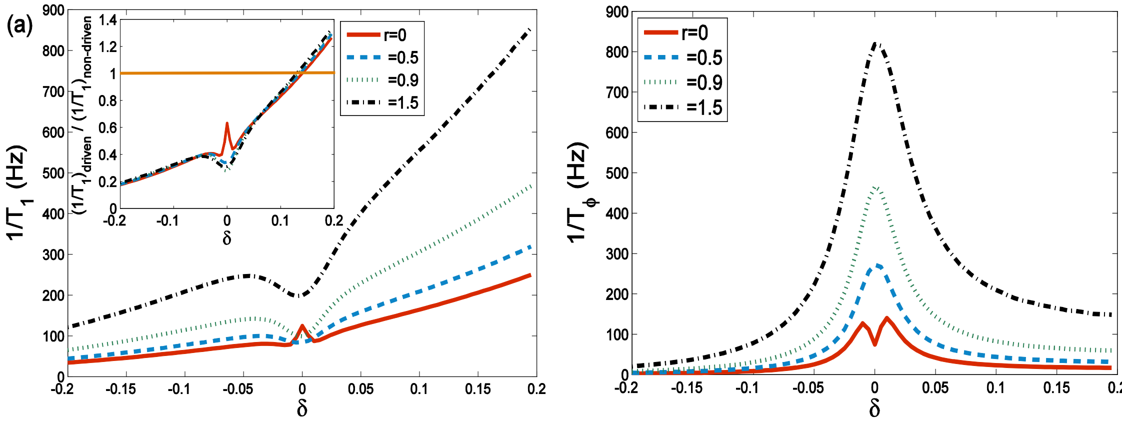

Fig. 5. Decoherence of a driven spin qubit. The left panel shows how spin relaxation rate changes with detuning of the driving field. The parameter $r = \alpha/\beta$ is the ratio of the Rashba and Dresselhaus spin-orbit interaction strength. As illustrated by the inset, the relaxation rate is lower than the non-driven rate for a wide range of driving field detuning. The right panel shows the pure dephasing rate for a driven spin qubit due to electron-phonon interaction. As is well known, for a non-driven spin qubit there is no pure dephasing due to phonon noise and spin-orbit interaction at the lowest order approximation. However, since driving changes the quantization axis of the qubit, now there could be pure dephasing, particularly when the driving field is near resonance.

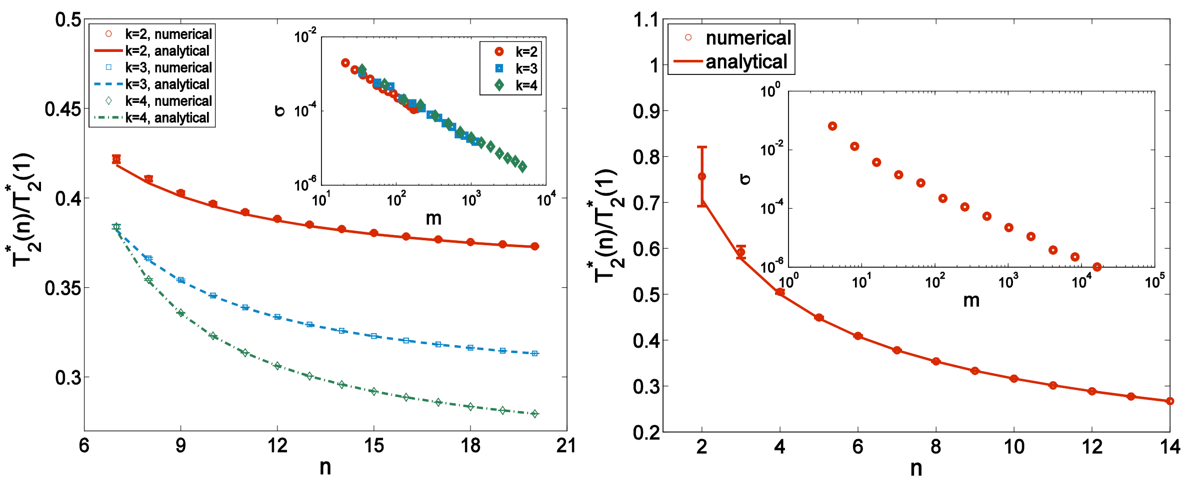

Fig. 6. Scaling of pure dephasing for uncoupled spin qubits. The left panel shows results on states with a specific spin polarization (represented by *k*, the number of flipped spin relative to the ground spin orientation). The *n*-qubit dephasing rate calculated from state fidelity is roughly proportional to $\left(n/k(n-k)\right)^{1/2}$ as compared to single-spin dephasing. Thus for large *n* and a constant *k* the overall decoherence grows only as $\sqrt{k}$ and does not increase with *n*. The right panel shows our results for a general n-qubit state. Now decoherence rate is proportional to $\sqrt{n}$, with the square root coming from the hyperfine induced pure dephasing channel. The insets for both panels show how fast the numerical errors decrease as we move to systems with more qubits. Specifically, the errors go down as a function of the Hilbert space size *m* instead of the number of qubits.

Figures

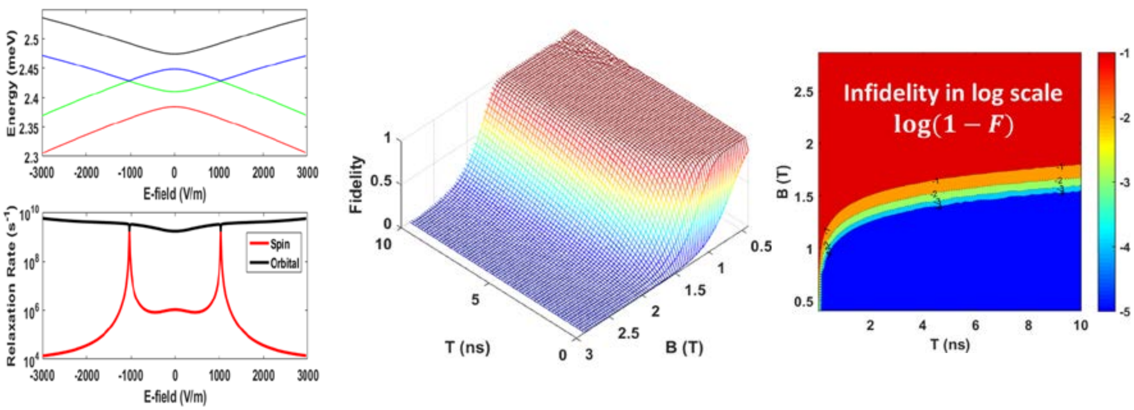

Fig. 7. Fidelity of a tunneling spin qubit in GaAs. The left panel shows the energy spectrum and spin relaxation rate as functions of the double dot detuning. When the spin-excited ground orbital state and the orbital-excited spin ground state anti-cross (the splitting due to spin-orbit coupling is small), strong spin mixing leads to a spin hot spot, as indicated by the sharp peaks in the lower figure. The middle panel shows the fidelity of spin transfer as a function of the total gate time and the applied field, if we vary the interdot detuning as a linear function of time. The right panel presents a different angle on the answer to the fidelity question, with the parameter regime below the orange belt giving high-fidelity spin transfer. This regime corresponds to relatively low magnetic fields and reasonably slow total gate time.

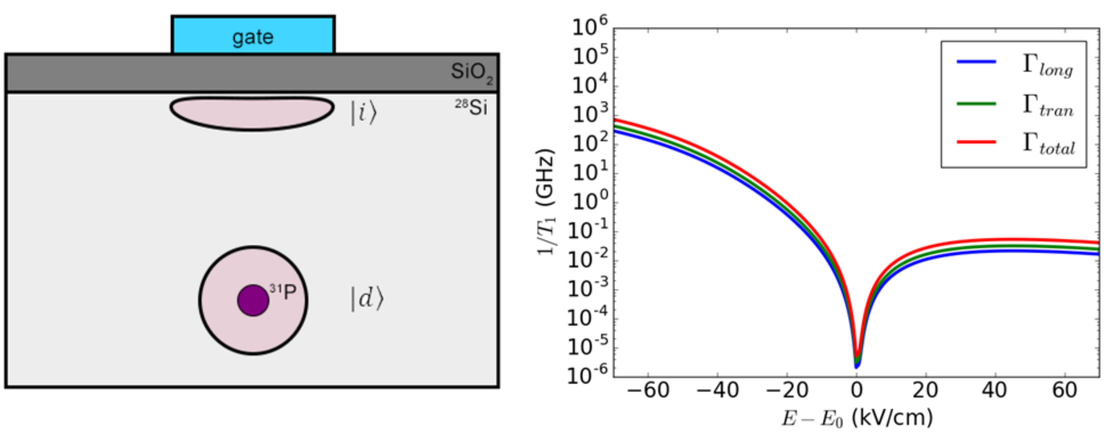

Fig. 8. Explorations on the donor-dot charge qubit and donor flip-flop spin qubit in Si. The left panel shows a diagram of the donor-dot system, with a single electron that can reside at both the donor and dot sites. When the electron is at the donor site, coupled to the donor nuclear spin through hyperfine coupling, it can form a flip-flop qubit (essentially an electron spin qubit) that has a very long coherence time. When the electron can hop between the donor and the dot, it forms a charge qubit that could interact with other charge qubits over a long distance, albeit with notoriously short charge decoherence times. We are now exploring whether we can use the not-so-coherent charge qubit to mediate a high fidelity coupling between spin qubits. The right panel shows our initial results on charge relaxation rate. The minimum charge relaxation happens when the donor and dot ground orbital states are in resonance. Further studies are underway to explore the form of the spin qubit coupling and its strength.