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Analyzing the fidelity of a singlet-triplet spin-orbit qubit in silicon using gate set tomography

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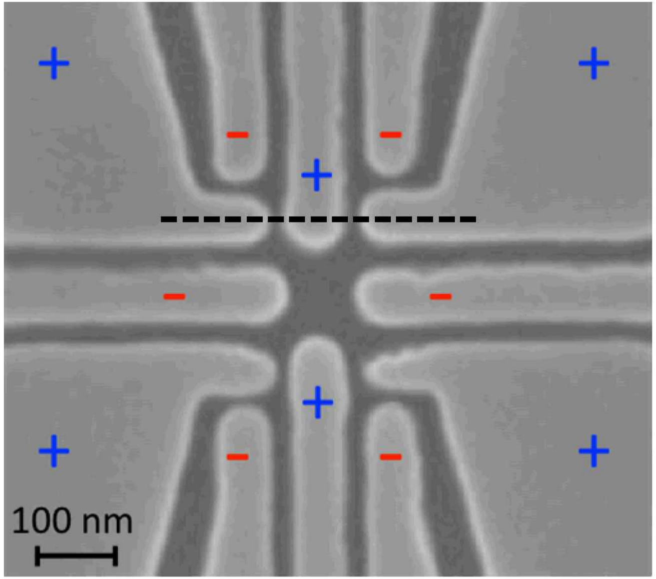
Outline

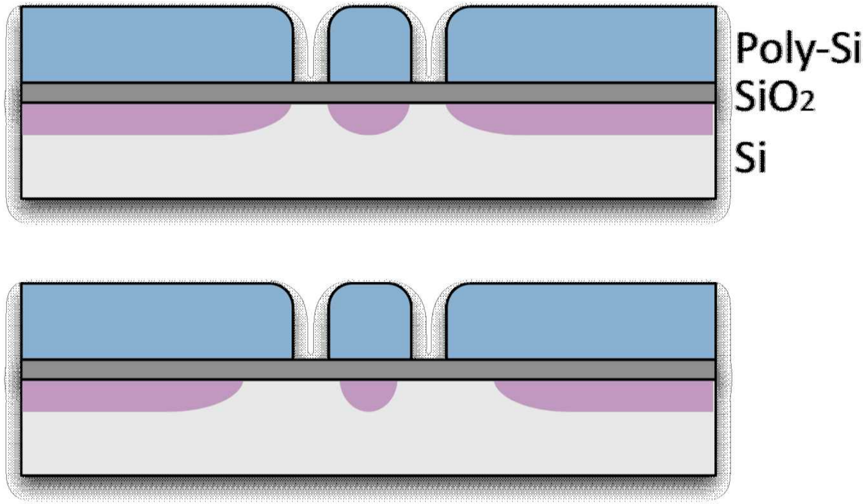
- Device geometry and tuning
- The singlet-triplet (ST) qubit
- Two-axis DC control of the ST qubit
  - Spin-orbit driven ΔEz rotations (x axis)
  - J rotations (n axis)
- Quality factor for rotations around n axis
- Gate set tomography (GST):
  - What is it? How does it work?
  - Initial results for DC gates
- Future work
  - AC control of the ST qubit
  - Strong AC driving

The Split Wire Accumulation Gate (SWAG) device



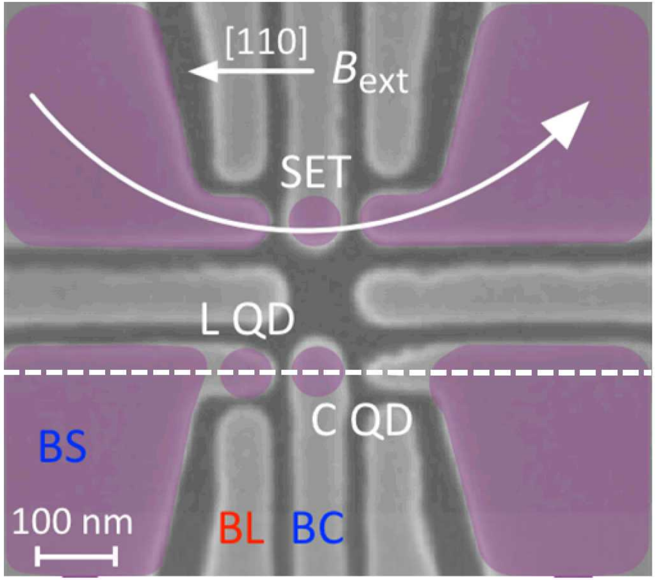
+ = accumulation gate
— = depletion gate

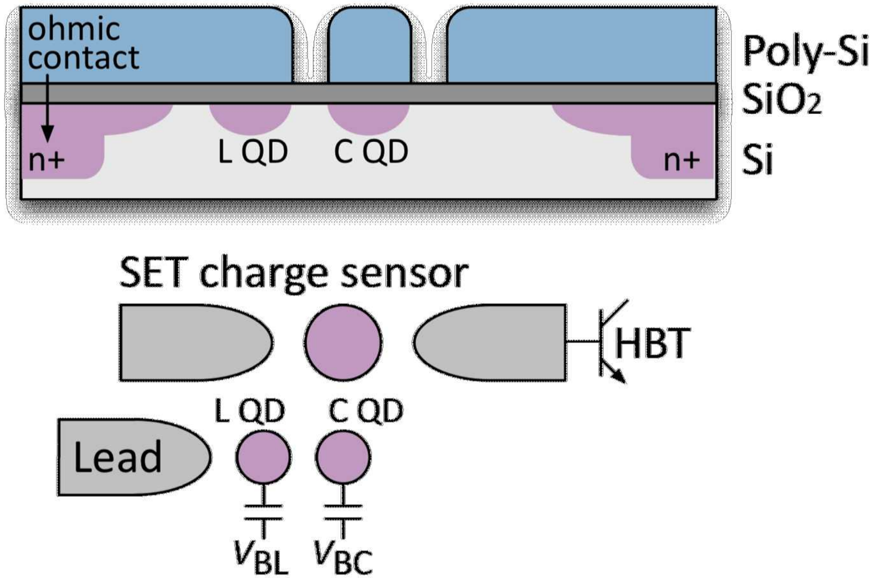
S. Rochette *et al.*, arXiv:1707.03895 (2017).



Both the accumulation and depletion gates can be used to control the number of electrons on the dot as well as the coupling between the dot and the leads.

Device tuning

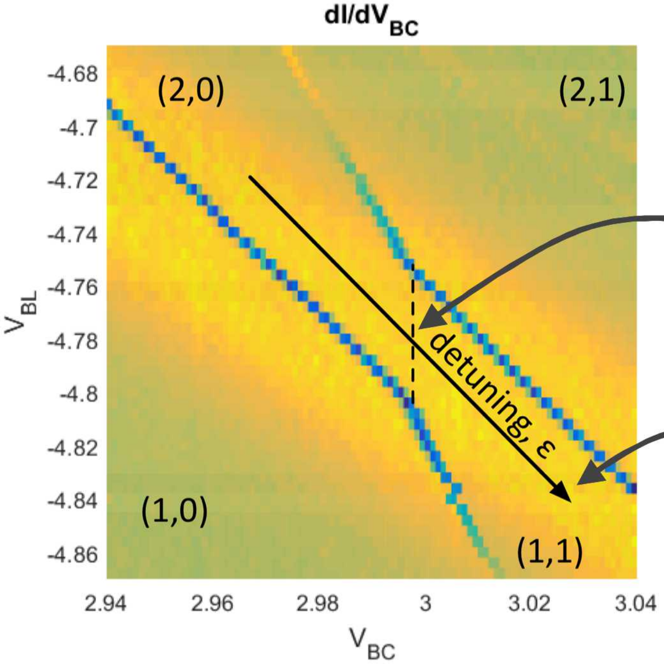




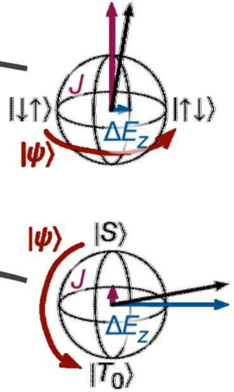
Only the left lead is used to couple to the dots. The electrons from the center dot must tunnel through the left dot to reach the lead.

The singlet-triplet qubit

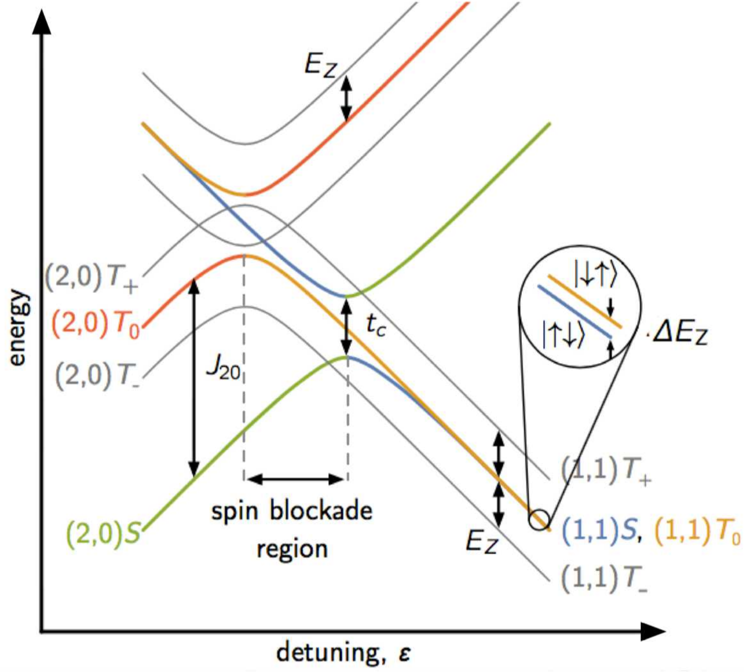
Charge stability diagram



$$\hat{H}_{ST} = -J(\epsilon)\frac{\hat{\sigma}_z}{2} - \Delta E_Z(\epsilon)\frac{\hat{\sigma}_x}{2}$$

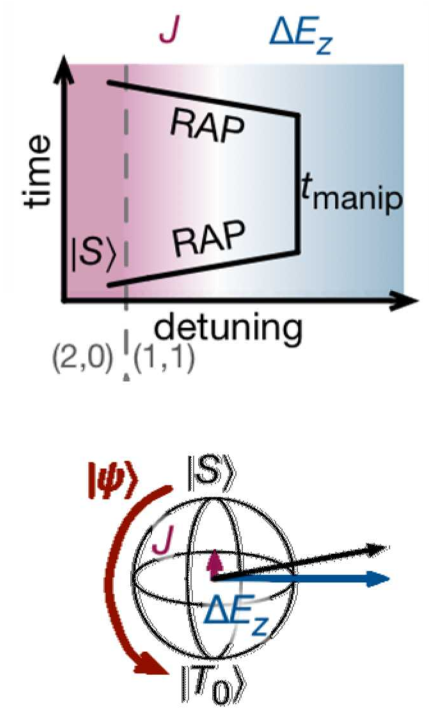


Energy level diagram

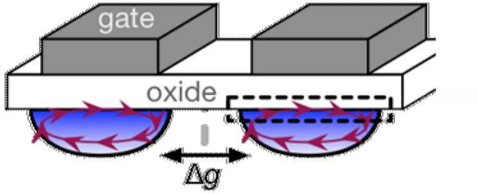


Readout is performed using latching method described in P. Harvey-Collard *et al.*, Phys. Rev. X **8**, 021046 (2018).

Two axis DC control: ΔEz rotations

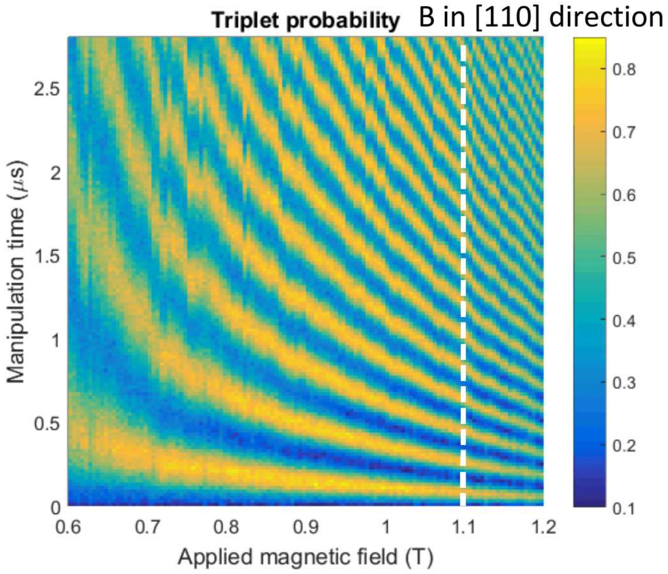


Spin-orbit effects



Spin-orbit interaction in each dot leads to a renormalization of their effective g-factors, which drives rotations of the form:

$$\Delta E_z = \Delta g \mu_B B_{ext}$$

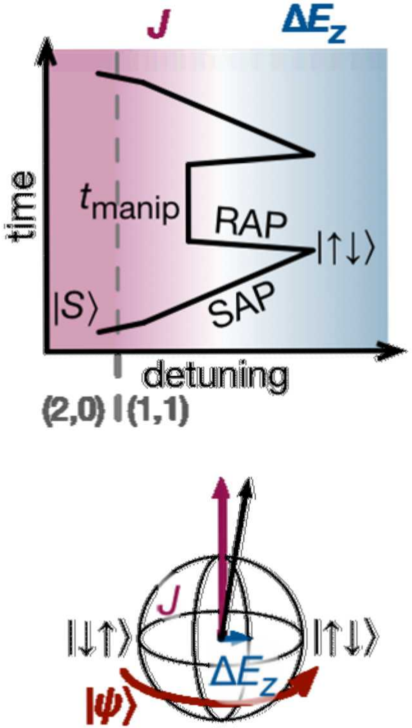


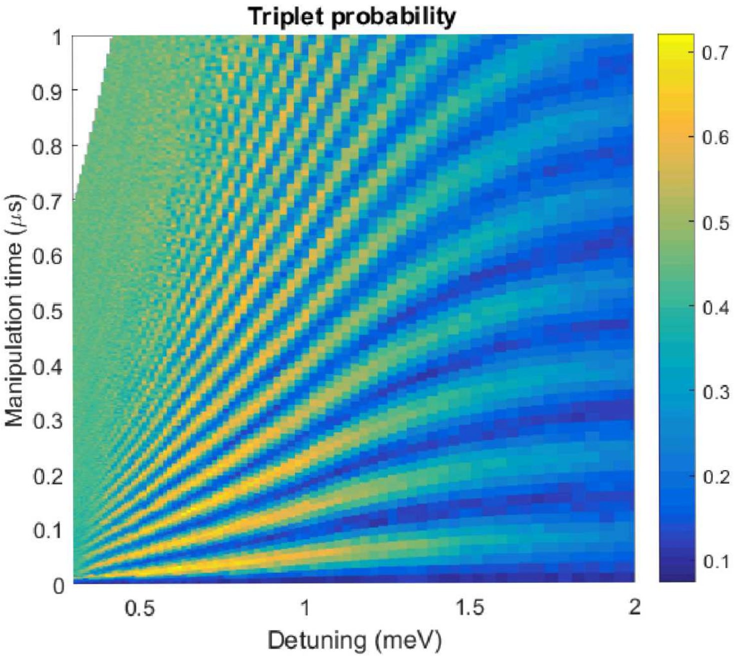
See presentation by N. Tobias Jacobson.

R.M. Jock *et al.*, Nature Communications **9**, 1768 (2018).

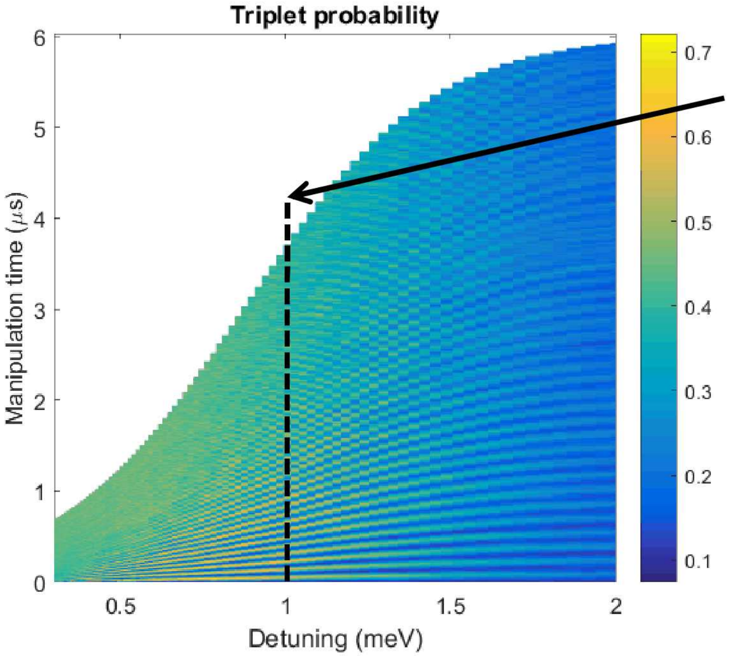
P. Harvey-Collard *et al.*, arXiv:1808.07378 (2018).

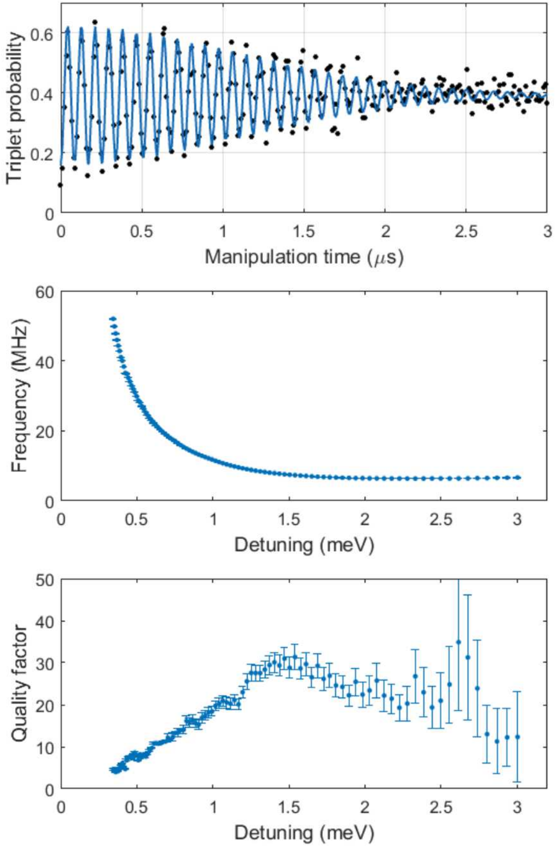
Two-axis DC control: J rotations





Characterizing gates: Quality factor





We define the quality factor as the number of **full rotations** within the decay time:

$$Q = f \cdot t_{decay}$$

For deep detuning, Q increases, but the angle between Gx (ΔEz axis) and Gn (J + ΔEz axis) decreases.

Question:
How should we characterize non-orthogonal gates?

Gate Set Tomography (GST)

What is GST?

It is a protocol that tries to infer the quantum operations a device (viewed as a black box) is performing by analyzing data generated by the device. It characterizes the quantum operations, state preparation, and measurement operations simultaneously.

What do you need?

1) **Target gate set**
   Ideal operations you want your device to perform (e.g. Gi, Gx, Gn)
2) **List of GST sequences**
   Corresponding to the target gate set. It is the list of experiments you need to run on your device.
3) **Data**
   Experimental outcome (counts) for each of the sequences in the list.

To construct the list of sequences, you need:

1) **Prep/Meas fiducials**
   For 85° between Gx and Gn:

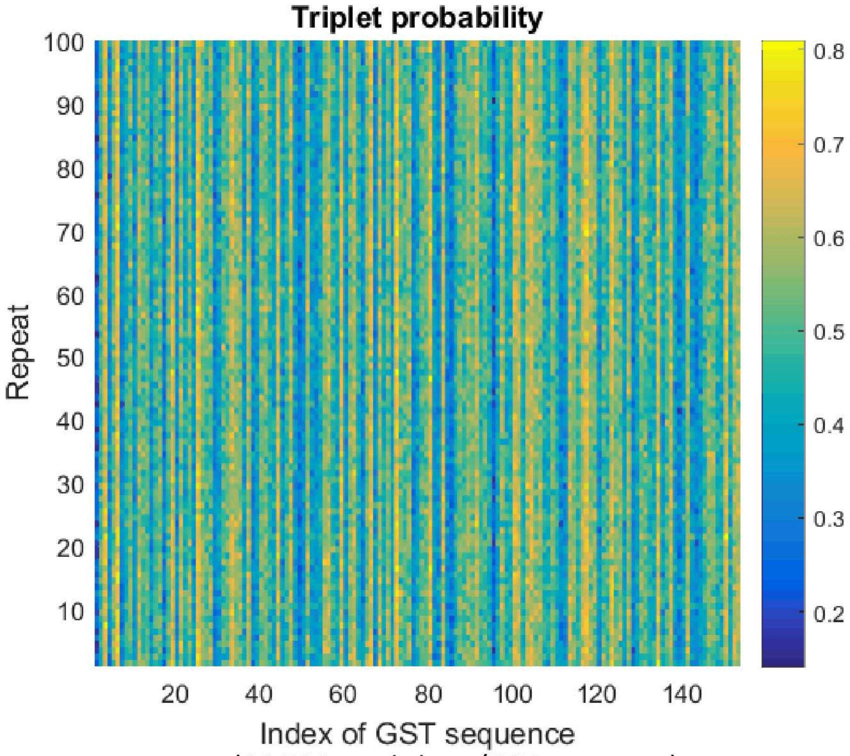
Prep	Meas
{}	{}
GxGnGn	GnGnGx
GxGxGnGxGnGx	GxGnGxGnGxGx
GnGxGnGxGxGx	GxGxGxGnGxGn

1) **Germs**
   For germs of length 2:
   Gi, Gx, Gn,
   (Gi)^2, (Gx)^2, (Gn)^2,
   GxGn, GxGi, GnGi

Gate Set Tomography (GST)

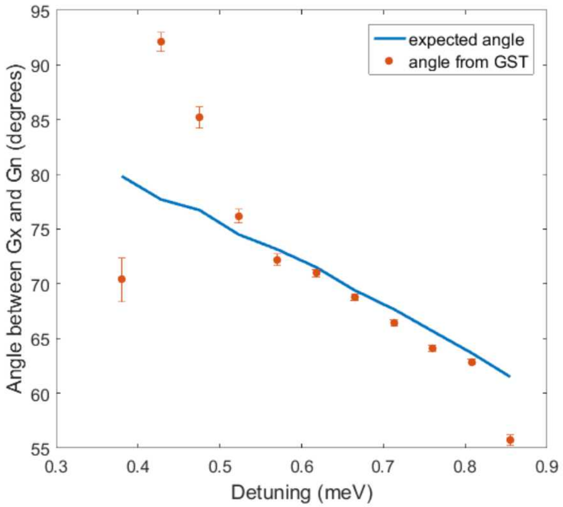
For 60° between Gx and Gn:

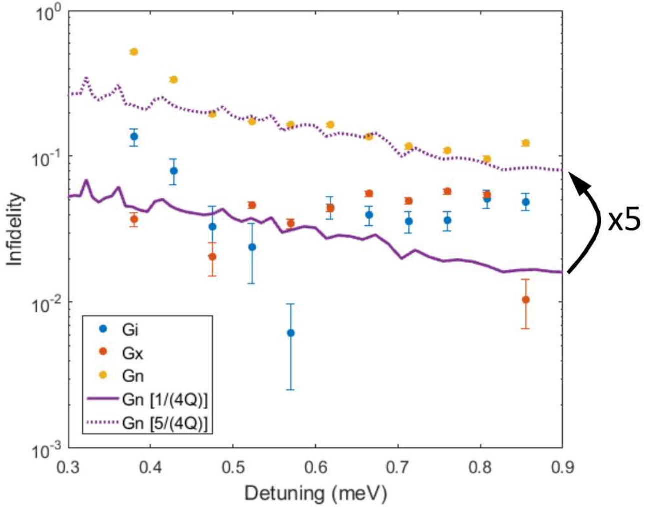
```
## Columns = ds_0 0 count, ds_0 1 count, [...]
{} 78 22 72 28 82 18
GxGn 57 43 57 43 56 44
GnGnGxGx 36 64 33 67 37 63
GxGxGxGnGnGn 75 25 76 24 65 35
GnGx 53 47 42 58 44 56
GxGxGnGn 31 69 31 69 23 77
GnGnGnGxGxGx 66 34 69 31 71 29
GnGxGxGn 48 52 55 45 56 44
GnGxGnGnGxGx 44 56 56 44 51 49
GnGxGxGxGxGnGnGn 52 48 66 34 62 38
[...]
GnGx(GxGn)GxGn 50 50 41 59 40 60
GnGx(GxGn)GnGnGxGx 53 47 54 46 55 45
GnGx(GxGn)GxGxGxGnGnGn 32 68 39 61 32 68
GxGxGnGn(GxGn)GxGn 37 63 34 66 26 74
GxGxGnGn(GxGn)GnGnGxGx 44 56 35 65 45 55
GxGxGnGn(GxGn)GxGxGxGnGnGn 47 53 47 53 41 59
GnGnGnGxGxGx(GxGn)GxGn 69 31 66 34 66 34
GnGnGnGxGxGx(GxGn)GnGnGxGx 43 57 36 64 50 50
GnGnGnGxGxGx(GxGn)GxGxGxGnGnGn 49 51 53 47 51 49
[...]
153 distinct sequences in this list
```



(10 000 total shots/GST sequence)

GST results for DC gates





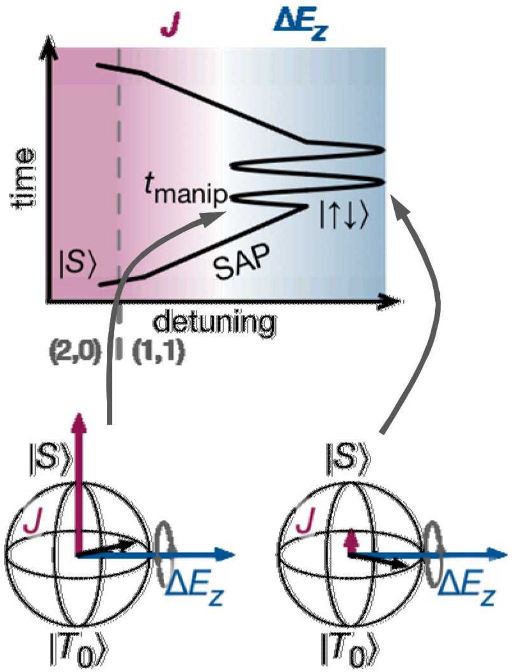
Questions:

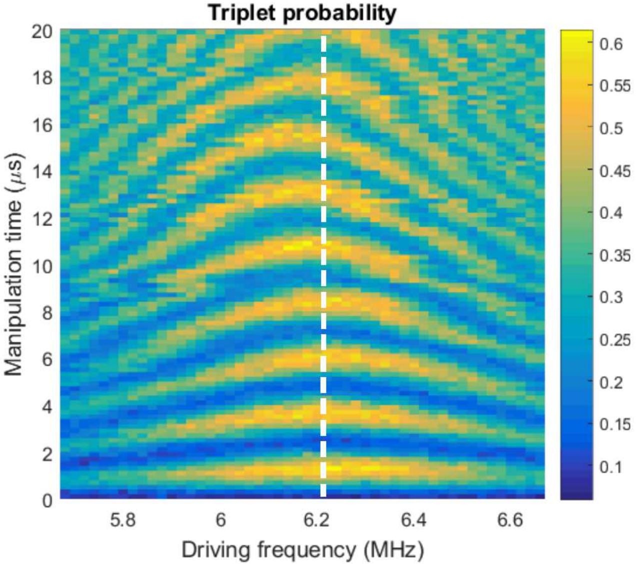
1) How much does the choice of fiducials affect the GST results?
2) How does non-Markovian noise affect GST results for non-perpendicular gates?
3) Can the results be significantly improved by increasing the number of fiducials/germs?

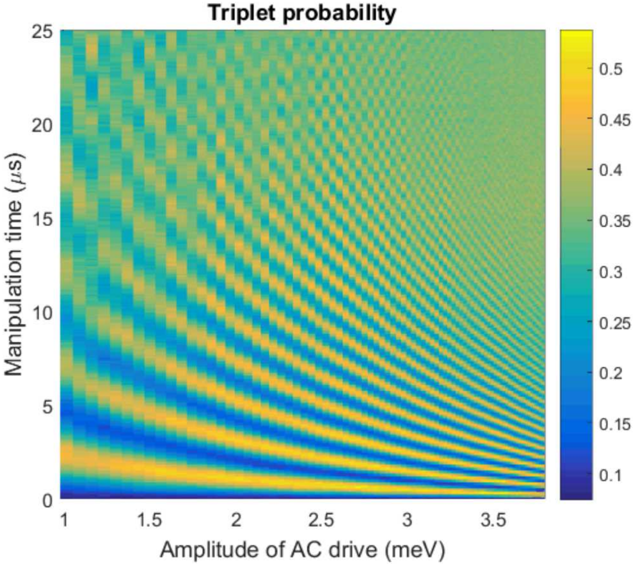
The questions above can be answered by performing GST analysis on simulated data.

<u>Future work on DC gates</u>: compose a Gy gate from Gx and Gn and perform GST on the orthogonal Gx and composite Gy gate set.

Future work: AC control

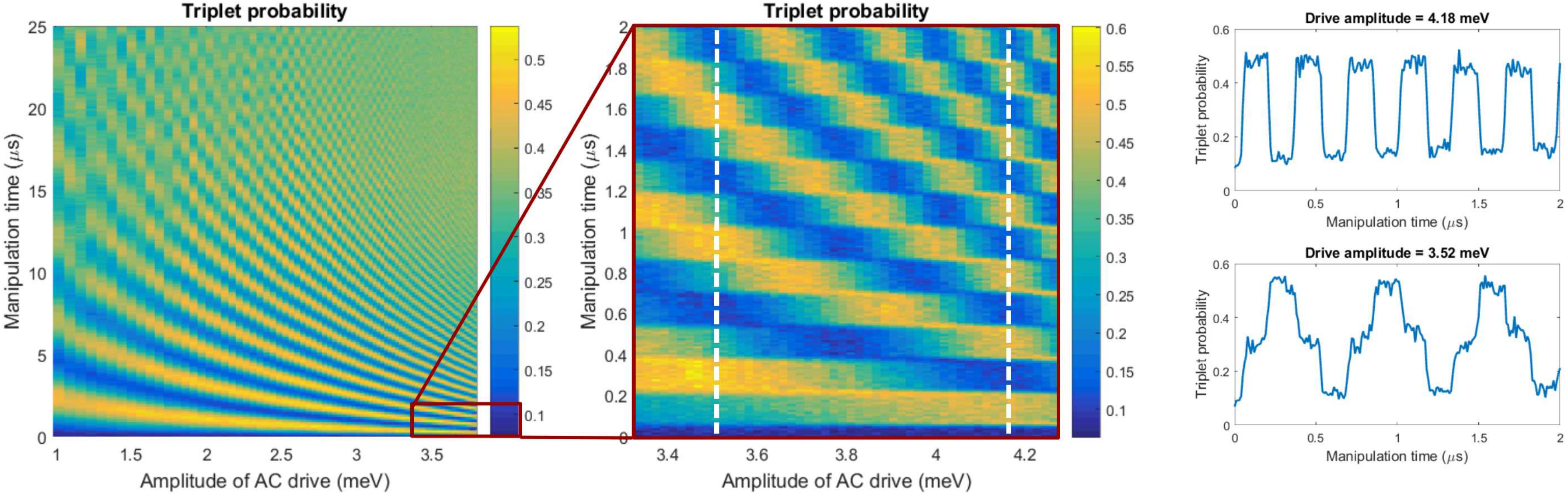






AC control naturally offers perpendicular Gx and Gy gates.
We will perform GST on AC gates and compare the performance to that of the DC Gx and Gn gates.

Future work: strong AC driving



Increasing the amplitude of the AC drive decreases the operation time of AC gates and is therefore expected to reduce the infidelity.

We will perform GST on AC gates for varying drive amplitudes to see if there is significant improvement.

Conclusion

- We use spin-orbit (SO) effects to drive rotations of our singlet-triplet (ST) qubit without the need for additional components such as micromagnets or microwave resonators.
- Several different modes of operation, some of which have non-orthogonal gates, are available for ST SO qubits and it is unclear which one offers the highest fidelity. These modes of operation include:
  - DC pulsing (at different detuning points)
  - AC pulsing (with different driving amplitudes)
- GST offers a consistent and quantitative way to characterize and compare these modes of operation.

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Sandia National Laboratories:
Dwight R. Luhman
Michael P. Lilly
Malcolm S. Carroll

U.S. DEPARTMENT OF ENERGY
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Quantum Information S&T
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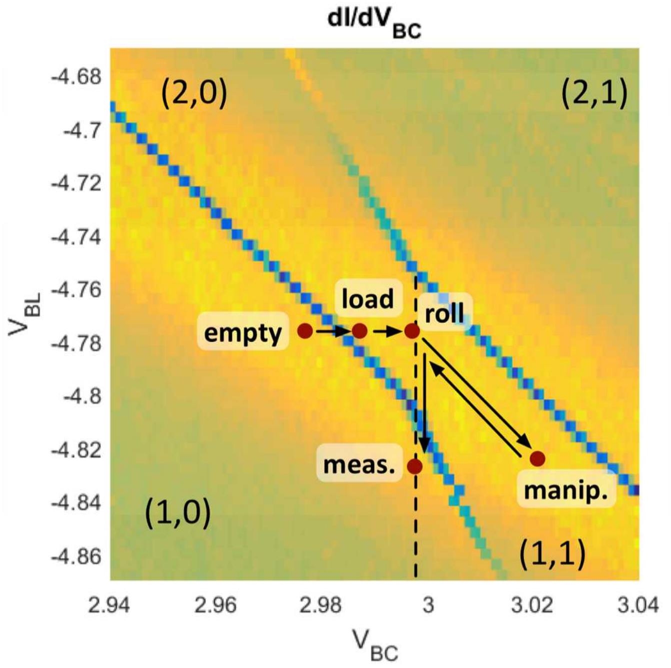
The singlet-triplet qubit

Charge stability diagram



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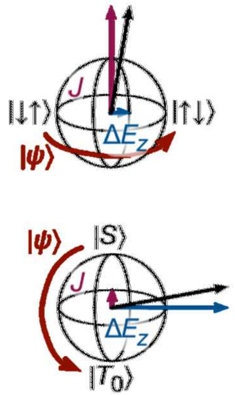

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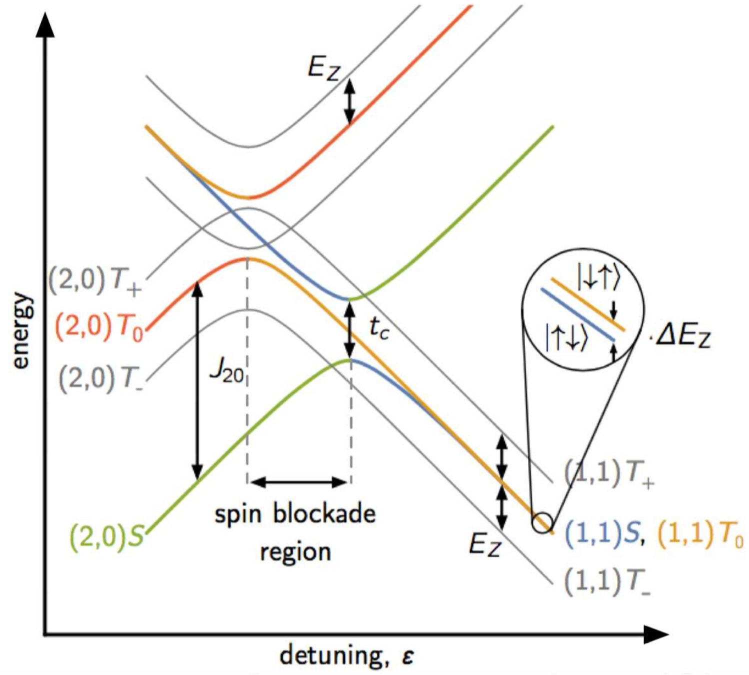

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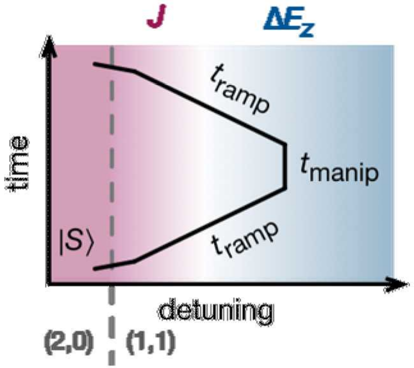
Initializing the qubit: rapid vs slow adiabatic passage

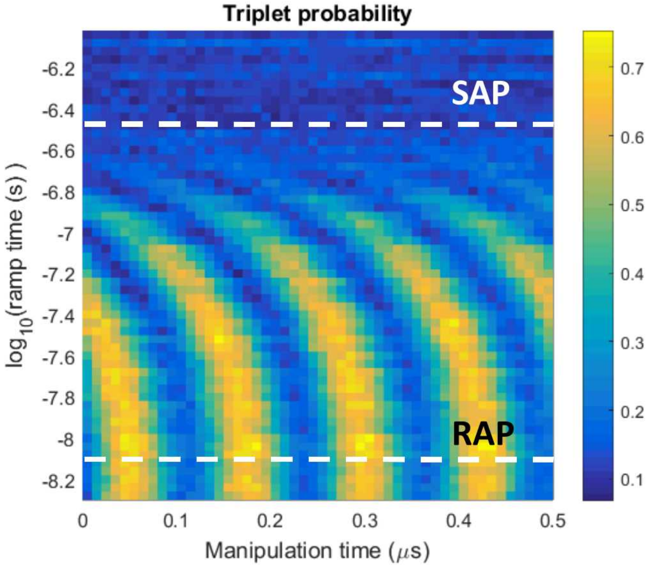
SAP: Slow Adiabatic Passage
Adiabatically with respect to both spin and charge.

$$|S\rangle \leftrightarrow |\uparrow\downarrow\rangle$$
$$|T_0\rangle \leftrightarrow |\downarrow\uparrow\rangle$$

RAP: Rapid Adiabatic Passage
Adiabatically with respect to charge. Diabatically with respect to spin.

$$|S\rangle \leftrightarrow |S\rangle$$
$$|T_0\rangle \leftrightarrow |T_0\rangle$$





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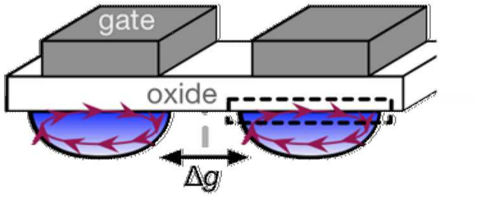

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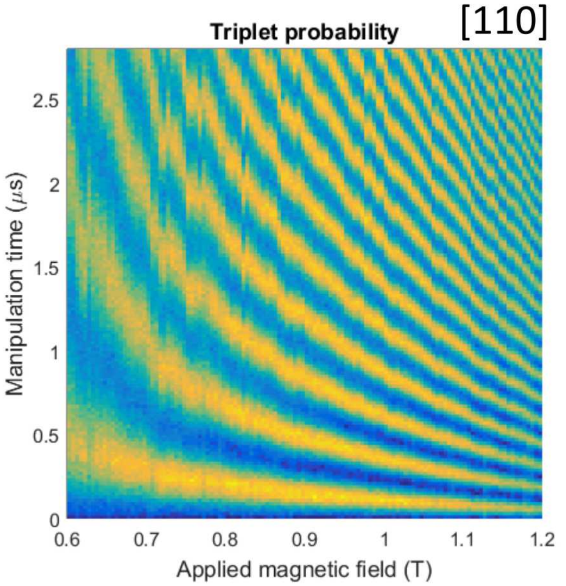

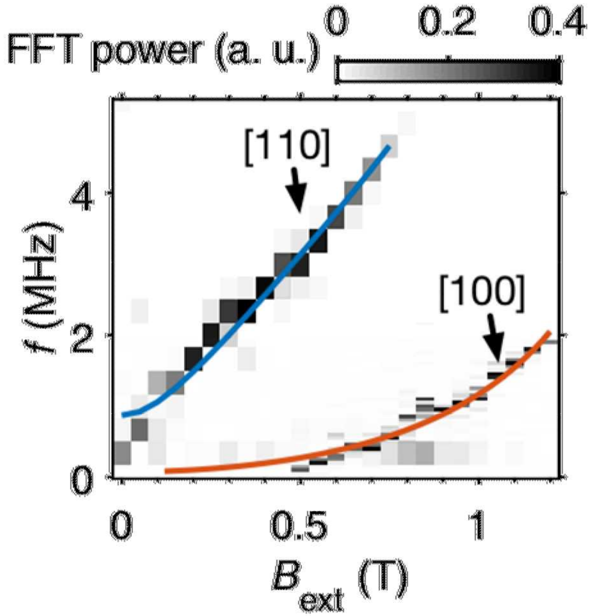

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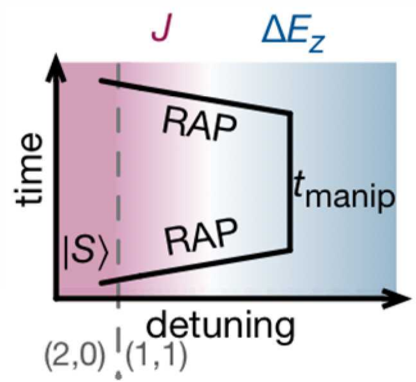
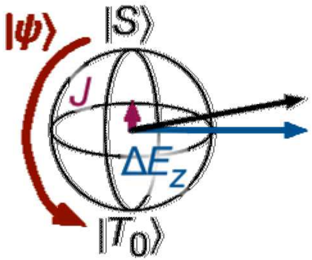
Two axis DC control: ΔEz rotations





B_{ext} = 1.1 T