Title: Lecture 7

Speakers: Crystal Senko

Collection: Many-Body States and Dynamics Workshop II

Date: June 13, 2019 - 11:30 AM

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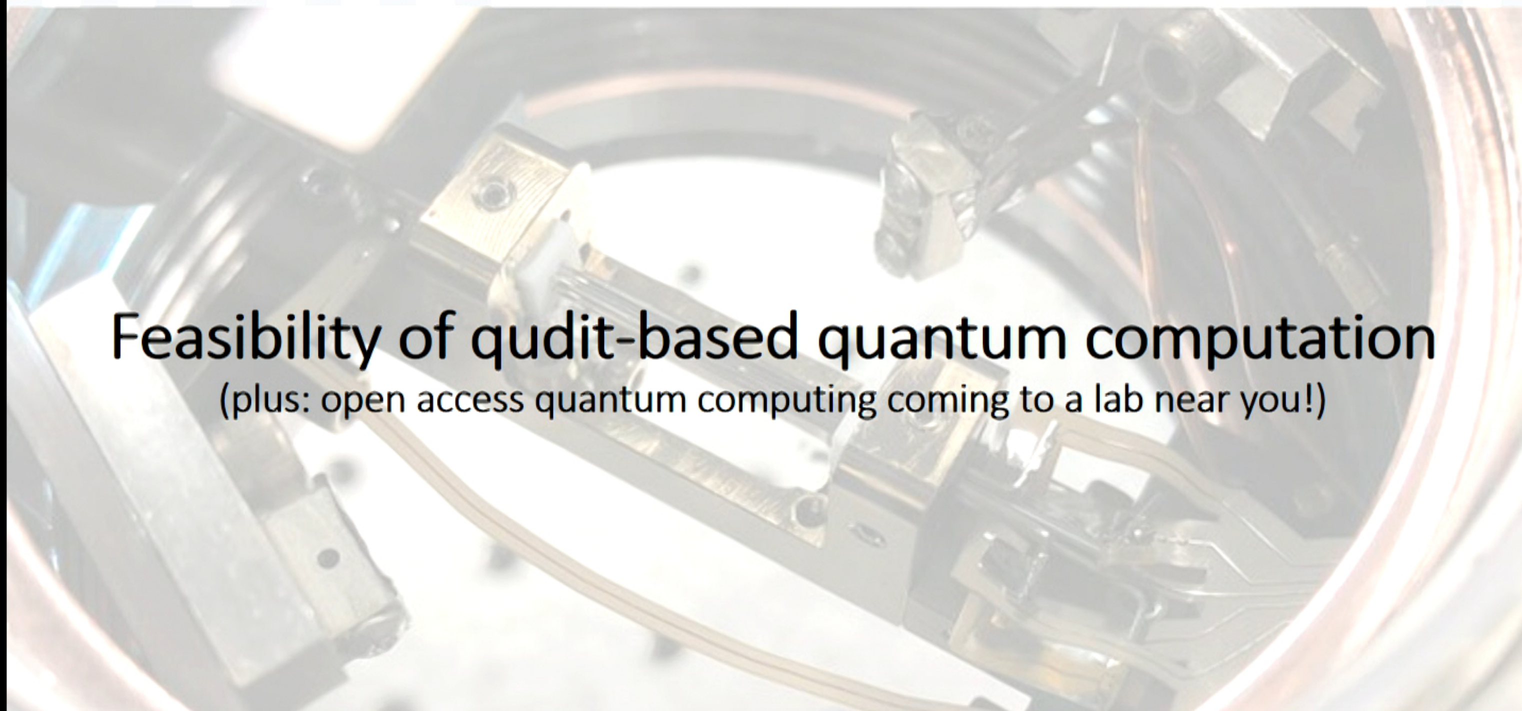


Feasibility of qudit-based quantum computation

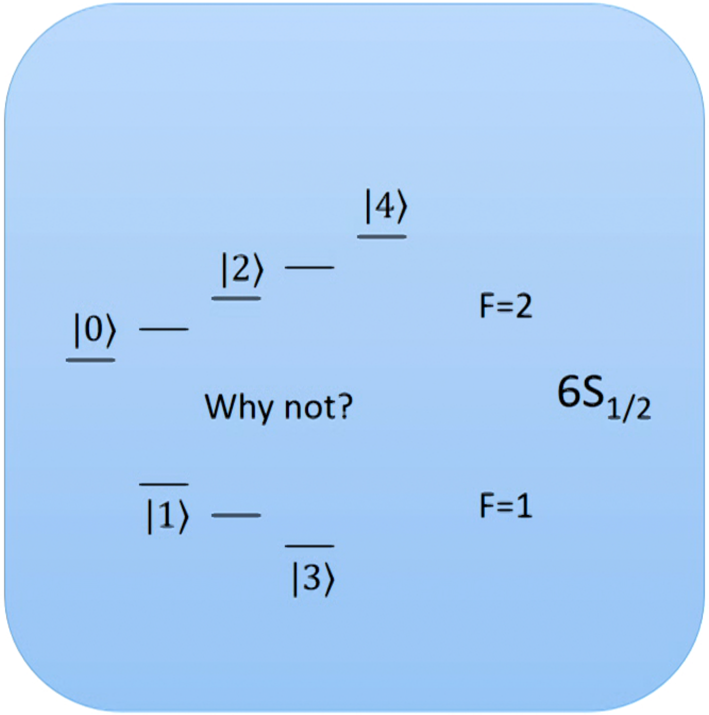
(plus: open access quantum computing coming to a lab near you!)

Crystal Senko
IQC-PI workshop
June 13, 2019


quantum computation
WATERLOO

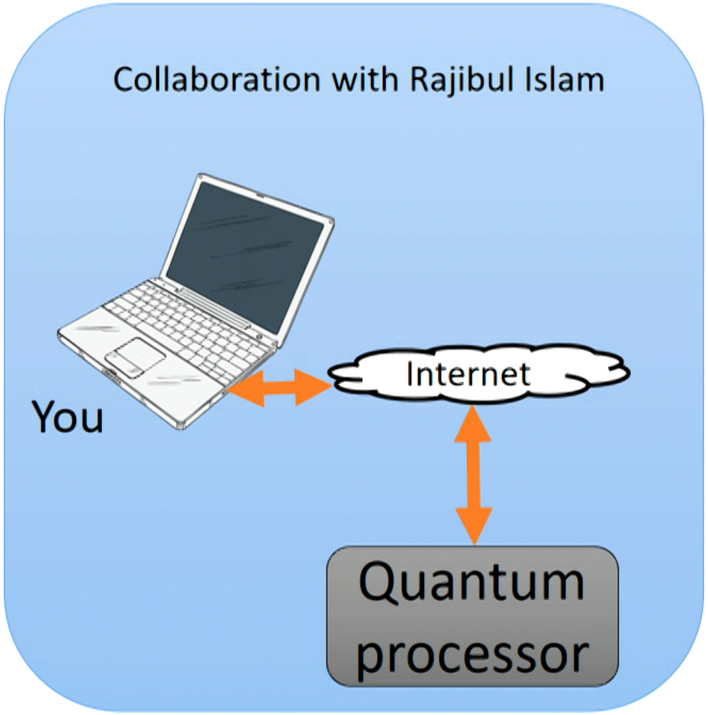
Themes of our research

Qudit based quantum computing



Open access quantum computing

Collaboration with Rajibul Islam



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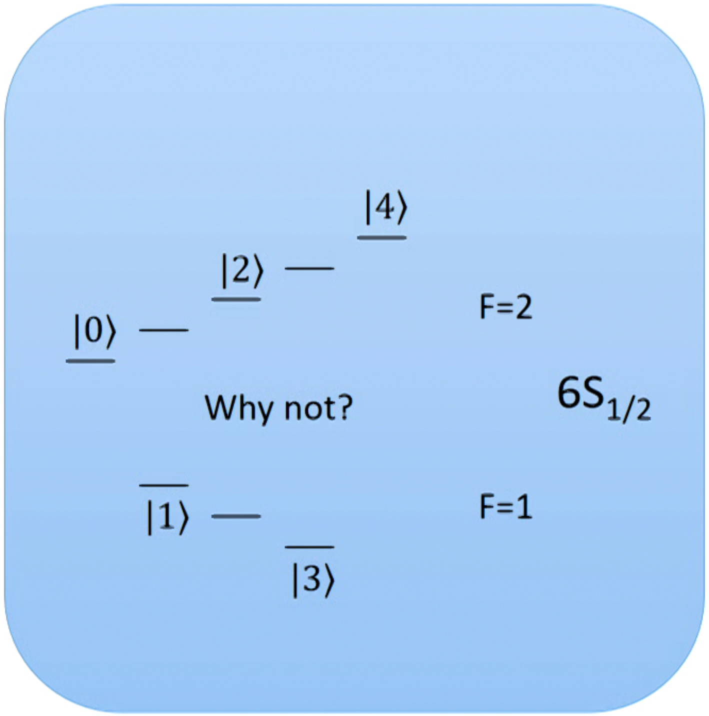

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To start: why qudits?

- Increase Hilbert space: 2^N (qubits) vs d^N (qudits)

$2^{10} = 1024$
$3^{10} = 59049$
$5^{10} = 9765625$

[2]Fedorov, A. et. al., 2011. *Nature, 481*(7380), 170-172. doi:10.1038/nature10713
[3]Parasa et. al., 2011, IEEE 41 https://doi.org/10.1109/ISMVL.2011.47
[4]Campbell, 2014, PRL https://doi.org/10.1103/PhysRevLett.113.230501
[5]Andrist et. al., 2015, PRA https://doi.org/10.1103/PhysRevA.91.042331
[6]Lanyon et. al., 2008, NaturePhysics https://doi.org/10.1038/nphys1150

To start: why qudits?

- Increase Hilbert space: 2^N (qubits) vs d^N (qudits)
- More efficient algorithm
  - Toffoli gate: 16 gates (2-level) vs 6 gates (3-level)[2]
  - More accurate quantum phase estimation[3]
- More forgiving error threshold for error correcting codes[4,5,6]

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Number of Ions vs d for QPE up to 5 Decimal Points

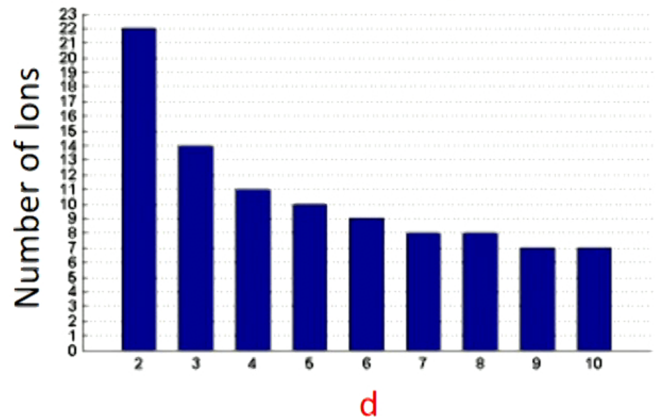

Figure adapted from [3]

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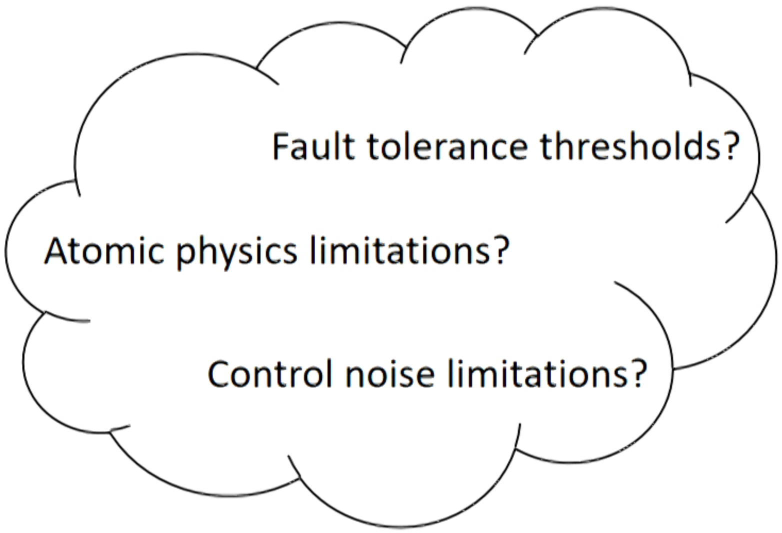

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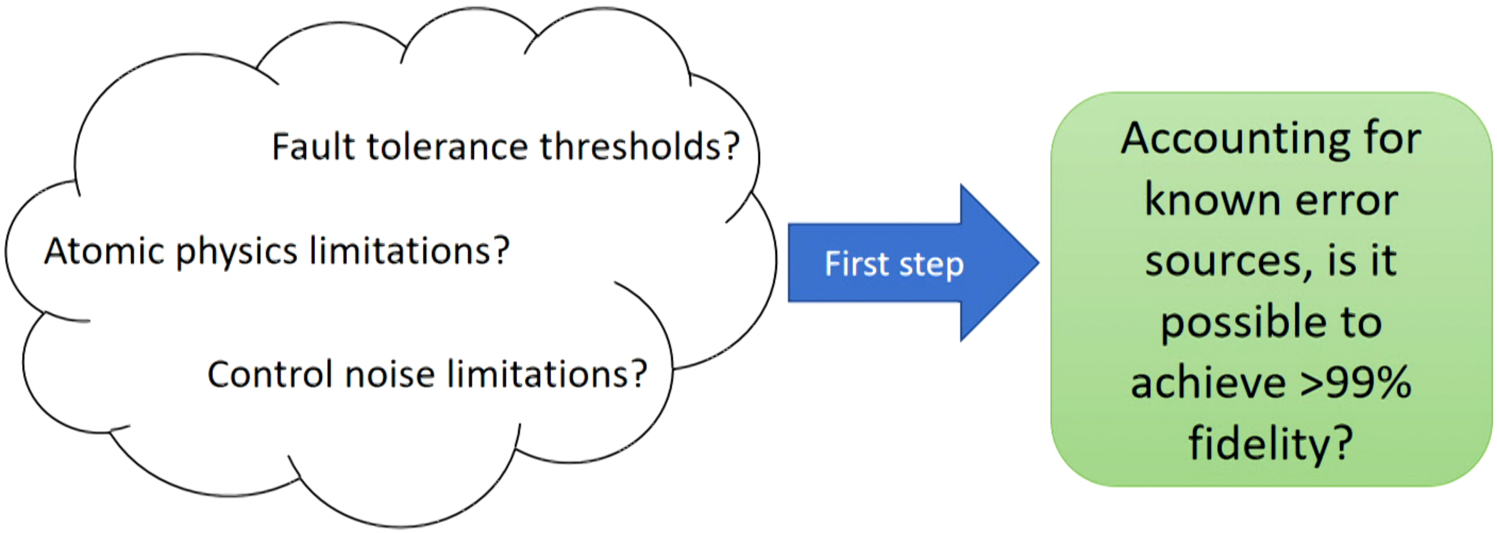

Caveats to our "fidelity" estimates

What we did here:
fidelity F

- Specific experimental protocol
- *Upper* bound on atomic structure limitations
- Upper bound on noise sources we don't know how to improve

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What we'll get in the lab: fidelity <F

- All the limitations we estimated, plus:
- Control noise that can be engineered out (voltage noise, etc)

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- *Upper* bound on atomic structure limitations
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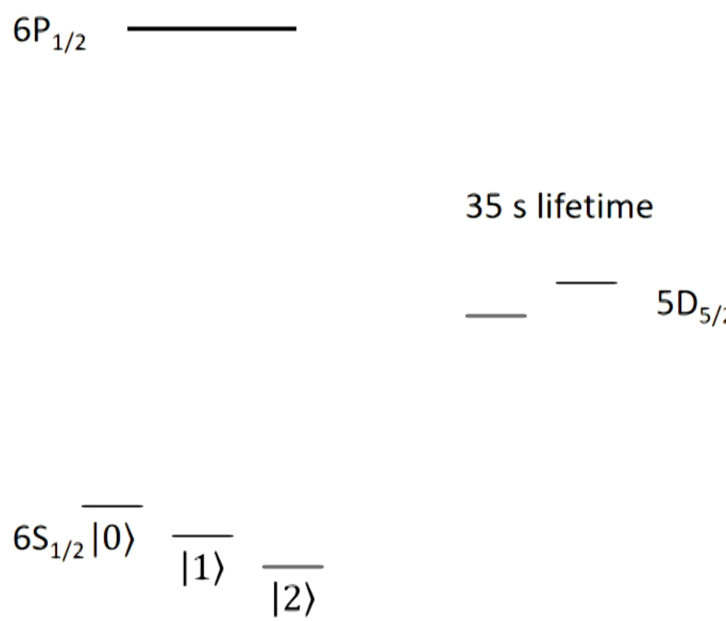
"Fundamental" limitations: fidelity probably >F

- Lots of parameters to optimize
- More clever protocols may be available

State Measurement

- Need more than one bit of information!

1. Shelve states in $S_{1/2}$ to corresponding metastable states in $D_{5/2}$ except for $|0\rangle$.
2. Collect fluorescence from all remaining states in $S_{1/2}$.
3. Bring back state $|1\rangle$ to $S_{1/2}$ level.
4. Repeat steps 2 and 3 for different states.



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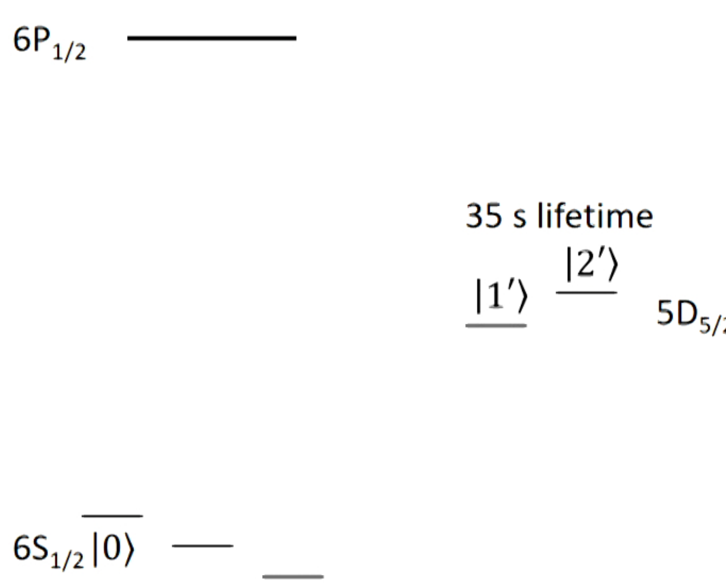

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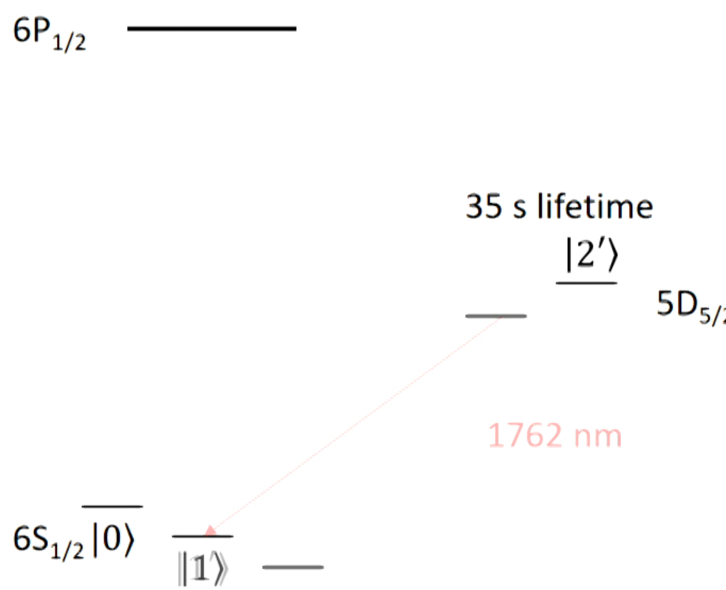

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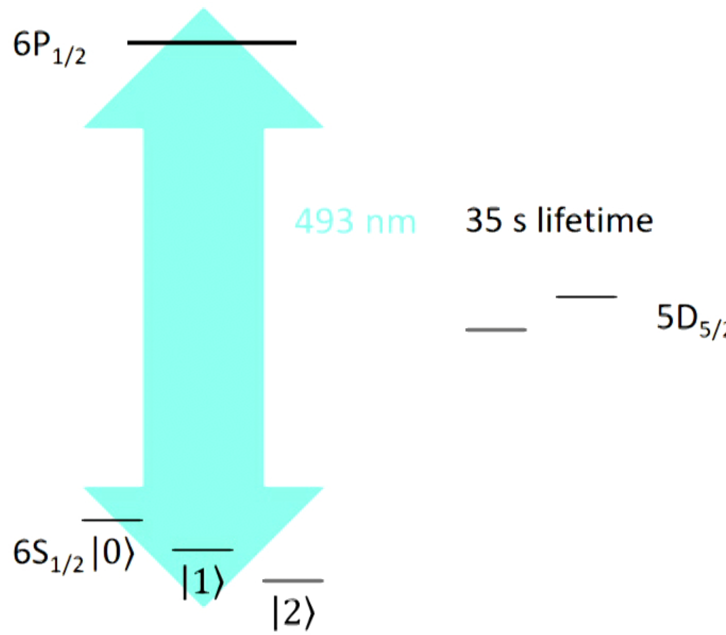
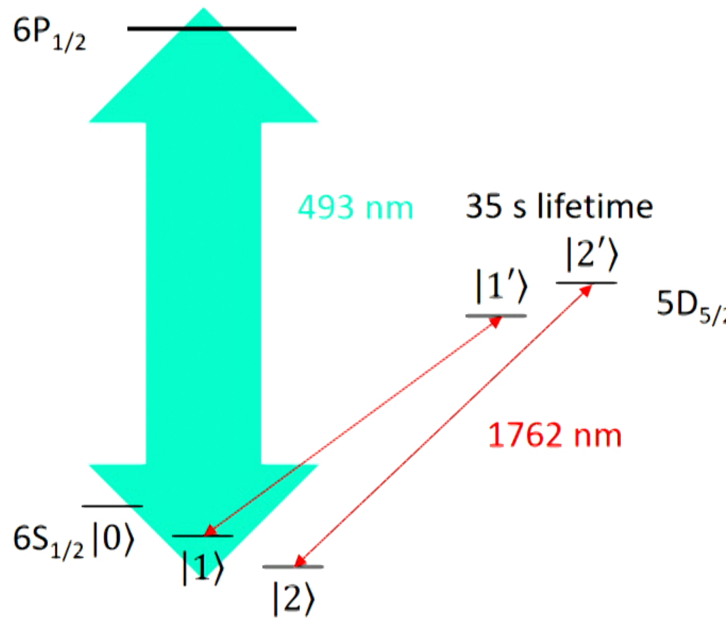


State Measurement

- Error sources:
  - Finite initial frequency detuning
  - Landau-Zener probability of diabatic transition
  - Dephasing due to laser linewidth
  - Off-resonant coupling

d (dimension)	Fidelity F	Error (1-F)
3	99.78%	2E-3
5	99.15%	8E-3
7	98.51%	1.5E-2



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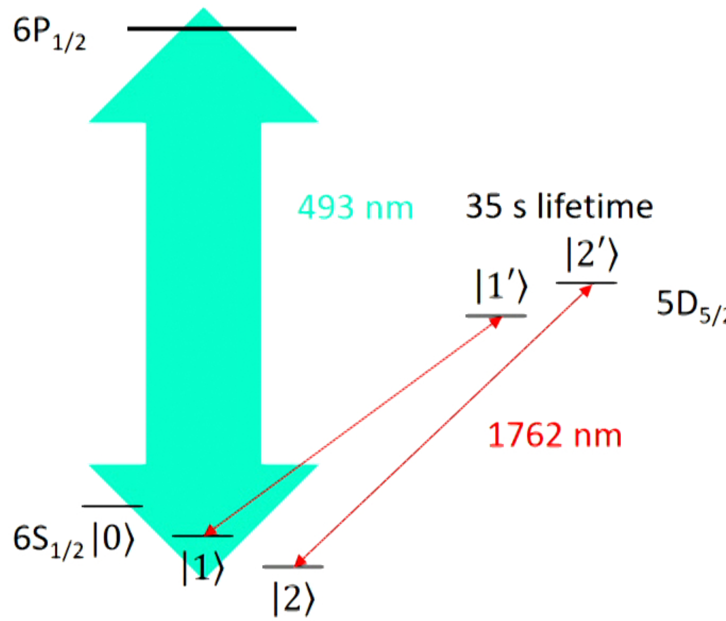


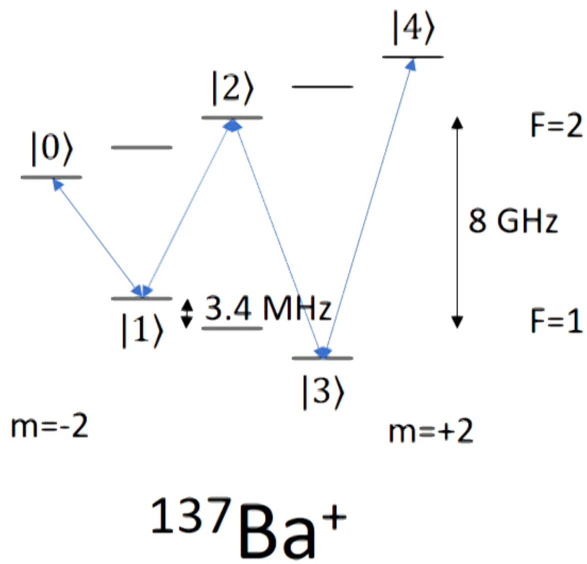
Single Qudit Gate

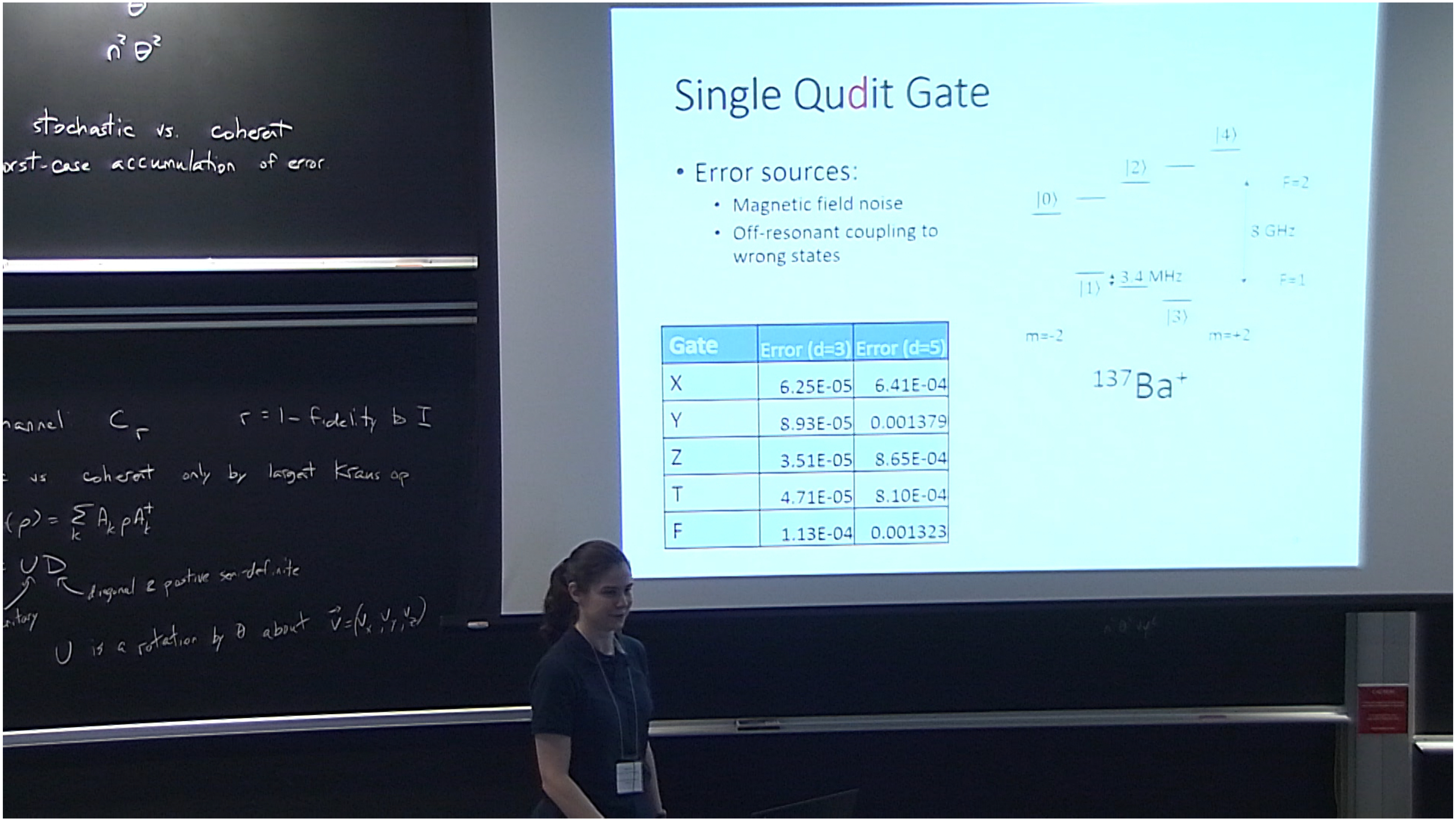
- With a fully connected graph, you can do any single-qudit unitary.
- Need $\frac{d(d-1)}{2} + 2(d-1)$ 2-level transitions

$$\hat{U} = \hat{V}_{d(d-1)/2} \dots \hat{V}_2 \hat{V}_1 \hat{D}$$

$$\hat{V} = \exp\left(i\theta\left(e^{i\varphi}|j\rangle\langle k| + e^{-i\varphi}|k\rangle\langle j|\right)\right)$$

Schirmer et. al., 2001, Journal of Physics A
stacks.iop.org/JPhysA/35/8315




Single Qudit Gate
• Error sources:
• Magnetic field noise
• Off-resonant coupling to wrong states
Gate | Error (d=3) | Error (d=5)
X | 6.25E-05 | 6.41E-04
Y | 8.93E-05 | 0.001379
Z | 3.51E-05 | 8.65E-04
T | 4.71E-05 | 8.10E-04
F | 1.13E-04 | 0.001323
|4⟩
|2⟩
|0⟩
F=2
3 GHz
|1⟩
3.4 MHz
|3⟩
F=1
m=-2
m=+2
137Ba+
stochastic vs. coherent
worst-case accumulation of error

Single Qudit Gate

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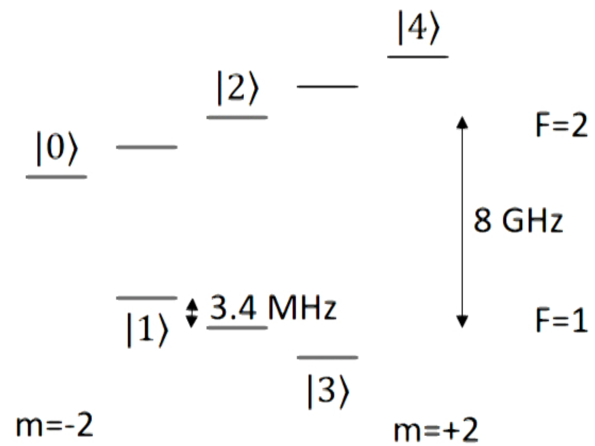

$^{137}Ba^+$

Entangling gate

- Laser-based gate protocol
- Interaction mediated by Coulomb forces
- Form of entangling gate (maps to SUM gate with single qudit operations):

$$U = \exp\left(i\theta\left[S_x^{(1)} + S_x^{(2)}\right]^2\right)$$

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Overall fidelity:

- 99.27% for $d = 3$.
- 32% for $d = 5$ (with experimental configuration we know how to implement)
- 96.6% for $d = 5$ (with a configuration we don't know how to do – could probably be improved)

Entangling gate fidelity

Error Source	d = 3	d = 5
Lamb-Dicke approximation	7×10^{-4}	5.8×10^{-3}
Rotating wave approximation	5×10^{-4}	2.2×10^{-3}
Spectator phonon mode	2.9×10^{-3}	1.26×10^{-2}
Photon scattering	8×10^{-4}	1.6×10^{-3}
Imperfect cooling	1×10^{-4}	2.7×10^{-3}
Motional heating	3.3×10^{-3}	4.6×10^{-3}
Magnetic field noise	$< 10^{-4}$	$< 10^{-4}$
Off-resonant frequencies	NA	6.8×10^{-1}

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Summary for qudits

- Possible to obtain 99% fidelity for 3-level qudits
- Higher dimensions may also be possible

	Fidelity		
d (dimension)	Measurement	Single-qudit gate	2-qudit gate
3	99.78%	99.98%	99.27%
5	99.15%	99.87%	32% (*96.63%)
7	98.51%	Not investigated	Not investigated

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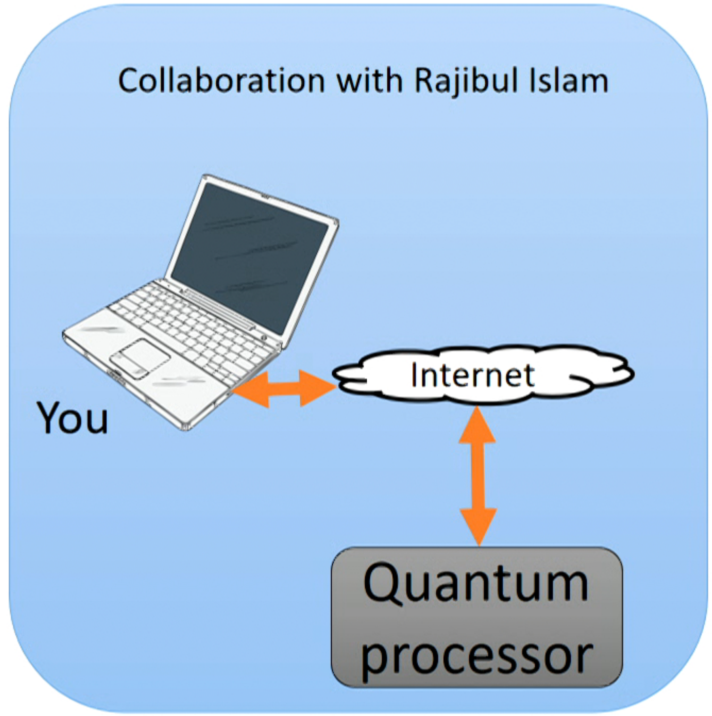


Overview of QuantumIon goals

- 10+ qubit ion trap quantum computer
  - Individual qubit control
  - Entangling gates between any pair of qubits
  - Proven architecture (see e.g. UMD, IonQ)
- Remote access platform
- Designed for multiple types of experiment

Quantum error correction

Quantum algorithms

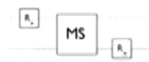
Pulse shaping, gate optimizations

Quantum optics, trapped ion physics

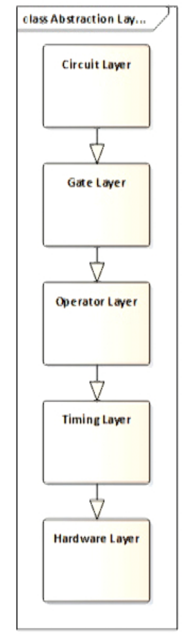
Many more

How to describe various controls?

- Desired Traits
  - Abstraction layers



Natural gate layer



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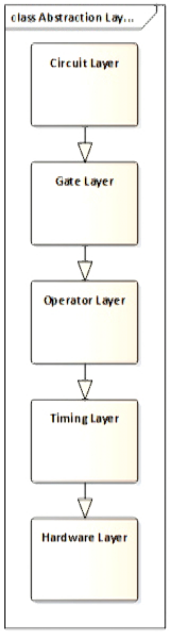
Logic gate layer



How to describe various controls?

- Desired Traits
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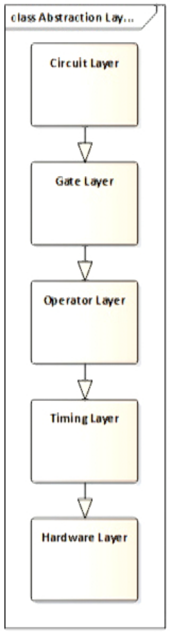
  - Sub-nanosecond timestamps of operation
  - Support for multiple languages (e.g. Python, Matlab, GUI???)
  - Strong separation between user code & QI machine code
  - Internal consistency



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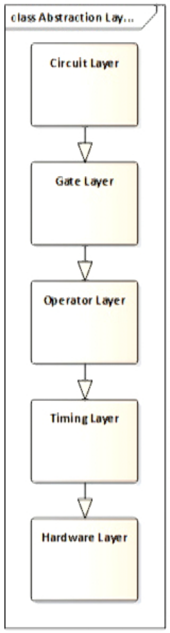
- Current languages (IBM, Google, Microsoft) insufficient
- New language of our own
  - Laser pulses are precision timed 'events'
  - Support classical/quantum decisions, loops, etc
  - Allocated resource strategy
  - XML Intermediate language
  - Support timing arithmetic on named constants (e.g. calibration params)
  - Function/macro definitions for design re-use & abstraction



Example User Code

```
// Example program a few pulses and AWG followed by a CCD image capture

// Begin by connecting to the machine this object will have all future transactions
qi = QuantumIon.connect("Username", "Password");

program = qi.CreateQuantumIonExperiment();             // create a new program
img = qi.AllocateQuantumIonImage();        // the CCD mesurement reports an image.  this allocates space
MyPulseShape = qi.CreateAWGWaveForm( qi, "mine.mat" );// same for AWG.  It is stored on the QI machine

program.AddSteps(       // Create program
[
      qi.CreateStandardTrapPrepStep(),                                 // ensures the trap is ready
      qi.CreateStatePrepStep( ),                                       // state preparation
      qi.CreateSimpleLaserPulseStep( 0.2, 0.3 ),                       // pulse @ t=0.2, duration 0.3
      qi.CreateSimpleLaserPulseStep( 0.8, 0.5*qi.cal.rabiperiod),      // pulse @ t=0.8, duration calculated
      qi.CreateAWGLaserPulseStep( 1.0, MyPulseShape ),                 // AWG pulse @ t=1.0
      qi.CCDRawImageMeasurementStep( 1.1, img )                        // CCD raw image and tag for saving later
]);


// perform 10,000 statistical averages
for(int n = 0; n<10000; n++)
{
      qi.QueueProgram( program );   // enqueue on machine
      qi.run();                     // run program

      result = img.download();
      DoStuffWithImage_IDontCareItsOnYourPCNow();     // post process
}
// done
qi.disconnect();
```

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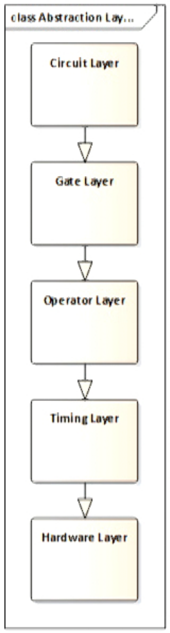

How you run an algorithm:

- Describe quantum program
  - “Get the trap ready”
  - “Prepare the qubits in |0>”
  - Apply laser pulse from t=100 us to t=200 us
  - …
  - Measure qubits at t=300 us

- Hand us the quantum program
- Download the measurement results

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Graduate students: Noah Greenberg, Rich Rademacher, Brendan White
Post-Doc: Matthew Day
Principal Investigator: Crystal Senko

- QuantumIon: collaboration with Rajibul Islam

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