

# Trapping Ions on a Shoestring?

As a proven architecture for quantum information experiments, it would be invaluable to establish a research program at an undergraduate liberal-arts college, building the opportunity for students to participate in state-of-the-art research in quantum information and quantum control. There are currently a number of research opportunities at undergraduate institutions that utilize laser cooling and that provide experiences in atomic physics, notably with Bose-Einstein Condensates. This project is trying to extend the research opportunity for undergraduate students in the field of trapped ion quantum information as well as covers the experimental implementation of a new type of quantum control using long-wavelength radiation.

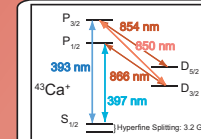
## Why Calcium?

The table at right is an inventory of all the trapable, single-electron atomic ions used in quantum information experiments. The different resonance transitions needed for Doppler-cooling and resonance fluorescence detection are shown. Simple Doppler cooling experiments for loading and detecting a single ion can currently be done most directly for calcium ions. Although some of the blue and UV diode lasers exist, the availability and price of those lasers are not consistent.

Ion	S <sub>1/2</sub> → P <sub>1/2</sub>	S <sub>1/2</sub> → P <sub>3/2</sub>	P <sub>1/2</sub> → D <sub>3/2</sub>	P <sub>3/2</sub> → D <sub>3/2</sub>	P <sub>3/2</sub> → D <sub>5/2</sub>	S <sub>1/2</sub> → S <sub>3/2</sub>	P <sub>1</sub> → Continuum
Ca	397	393	866	850	854	729	423
Sr	422	408	1092	1004	1033	674	460
Ba	493.5	455.5	650	585.5	614	1760	553
Be	313	313	-	-	-	-	235
Cd	226	215	-	-	-	-	229
Mg	280	279	-	-	-	-	285
Yb	369	-	935	-	-	-	399
Hg	194	164	-	-	-	-	185
Zn	203	206	-	-	-	-	213

Laser wavelengths (in nm) are given for the possible trapped ion quantum information atomic species. The **BOLD ITALIC** wavelengths are accessible via direct diode lasers, while the **ITALIC** wavelengths can be reached by frequency doubled diode lasers.

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Calcium has also been proven in trapped ion quantum research. There are several groups including the Steane Group at Oxford, the Blatt Group at Innsbruck, and Drewsen Group at Arhaus that currently work with trapped calcium ions. In addition, there has been work done with both <sup>40</sup>Ca<sup>+</sup> and <sup>41</sup>Ca<sup>+</sup> qubits.

## Experiment Setup

**Ophir Laser Power Meters**  
1 UV head  
1 IR head  
Cost: \$1200

**Dual-monitor Computer controller:**  
CCD Camera  
Wavemeter Read-out  
Vacuum Pressure monitor  
Cost: \$1000

**Thorlabs Gold Mirrors**  
Wavelength 866 nm  
R ~ 90%  
Cost: \$100

**Custom Blue Optical Cavity**  
FSR: 125 MHz  
Wavelength: 400 nm  
With piezo driver and PMT  
Cost: \$500

**Copper Helical Resonator**  
Resonance: 20 MHz  
Q-factor: 150

**Isomet 8W Amplifier**  
HP8640B Signal Generator  
Analog Oscilloscope  
Cost: \$800

**Special Optics**  
Lens 54-17-30-397nm  
Focal Length: 30 mm  
Back Focal Length: 20 mm  
Cost: \$700

**XYZ Translation Stages**  
Laser Beam Positioning  
Camera Lens Positioning  
Cost: \$2000

**Thorlabs Lens Tubes**  
Lens Doublet (400 nm)  
Cost: \$600

**SBIG**  
ST-402 ME CCD Camera  
TE Cooled CCD  
QE ~ 40% at 400 nm  
Pixel Array: 765 x 510  
Number of Pixels: 390,000  
Pixel Size: 9µm  
CCD Size: 4.6mm x 6.9mm  
CCD Area: 32mm<sup>2</sup>  
Dark Current at 0 C: 1e-/p/s  
Read Noise: 17e-  
Full Well Capacity: 100,000 e-  
Computer Interface: USB 2.0  
Full Frame Transfer: 0.8 sec  
Cost: \$1700

**Coherent Wavemeter**  
Precision: 0.001 nm  
Fiber-optic input coupled  
Auto-calibration  
Cost: \$10,000

**Thorlabs Lens Tubes**  
Lens Doublet (400 nm)  
Cost: \$600

**Next Generation Vacuum System**  
Fall 2007  
Cost: \$10,000

**Optica Blue Diode Laser: DL100 with controller**  
Wavelength: 397.847 nm  
Mode-hop free tuning range: 10 GHz  
Cost: \$19,000

**Bomco quartz vacuum window**  
Bakeable and fused directly to steel  
Clear front window  
Cost: \$1300

**Varian/Duniway**  
8 L/s Ion Pump  
High voltage controller  
Bakeable Cable  
Cost: \$2200

**Optica IR Diode Laser: DL100 with controller**  
Wavelength: 866.214 nm  
Mode-hop free tuning range: 15 GHz  
Cost: \$11,000

**New Focus**  
5100 UV mirrors  
Wavelength: 397 nm  
R ~ 99%  
Cost: \$300

**Homemade electron gun**  
Filament  
Ceramic tube  
Assorted stainless steel parts  
Cost: \$200

## Budget to Date

Lasers:	\$30,000
Laser Measurement and optics:	\$16,100
Vacuum System and RF:	\$5,200
Imaging System:	\$4,000
<b>Total Cost to Date:</b>	<b>\$55,300</b>

Working on trapping ions at an undergraduate liberal-arts college: *Priceless*

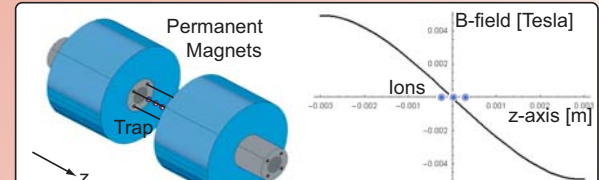


**SAES ST172**  
Passive pumping  
Nonevaporable getter  
Run during bake-out  
Cost: \$200

**Natural Calcium source**  
Stainless steel hypodermic needle  
Stainless steel leads  
Cost: \$400

**Tungsten wire**  
Double loop  
Stainless steel rods  
Cost: \$100

## Future Direction: Magnetic Field Gradients



One research objective is to combine a line of ions with a strong magnetic field gradient. The magnetic field shifts the ground state energy levels in an odd-numbered isotope like <sup>43</sup>Ca<sup>+</sup>. This makes the line of ions look like a molecule for Nuclear Magnetic Resonance (NMR) studies. But the interactions in this "molecule" can be tuned and adjusted and more ions can be added, unlike the real chemical molecules in NMR. By controlling the characteristics of the ion "molecule", it will be possible to build a designer entangled system.