A high-flux source of laser-cooled strontium atoms

Oxford Physics:
Chris Foot, Elliot Bentine, Sean Ravenhall, Leo Xu, & Peter Zhou
Key stages:
1. Source of neutral strontium atoms
   - Oxf or MAGIS?
2. Two stages of laser cooling
   - Oxf/NPL
3. Transport into vertical tube (injection)
   - Cam
3a. Further cooling?
   - TBD
4. Launching (acceleration)
   – copy MAGIS?
5. ToF - interferometer sequence
6. Detection – CCD camera

AOIN-10: sub-assemblies

CAD in the pre-proposal (E.Bentine, June 2019)
AION-10: Temperature vs. Number/second (Sr-87?)

- **770 \( \mu \text{K} \) = Doppler cooling limit (461 nm) blue**
- **1 \( \mu \text{K} \approx \) cooling limit (689 nm) red (a few \( \mu \text{K} \))
- **800 K = oven temperature – strontium source**
- **0.18 \( \mu \text{K} \) = Doppler cooling limit**
- **0.23 \( \mu \text{K} \) = Recoil limit

**Transport**
- AION-10 - initial
- AION-10 upgraded

**Questions**
- Transport without heating?
- Evaporative cooling?
- Delta-kick (adiabatic) cooling

**Improvements**
- x100 higher flux \( \Rightarrow \) x10 improvement in sensitivity
Source laser-cooled strontium atoms
(Oxford and NPL)

2D MOT cold-atom source

To replace Zeeman slower on existing set ups

Loading a 3D MOT

Our current capabilities
- NPL Sr lattice clock
Atom source: sodium (Trento, Italy)

– permanent magnets for Zeeman slower and 2D MOT
– Commercially available

Compact high-flux source of cold sodium atoms
Lamporesi, G. … and Ferrari, G., (2013)
Rev. Sci. Instrum., 84, 063102

Direct comparison between a two-dimensional magneto-optical trap and a Zeeman slower as sources of cold sodium atoms.
Laser Physics Letters, 13, 065501
Atom source of strontium @ Shanghai, China with team members from Heidelberg

“atomic flux exceeding $10^9$ atoms/s without indication of saturation”

Two-dimensional magneto-optical trap as a source for cold strontium atoms
I. Nosske, ... M. Weidemüller (2017)
Phys. Rev. A 96, 053415
A high-flux source of laser-cooled strontium atoms: Oxford Physics

2D MOT cold-atom source

Principle of 2D MOT source

Stainless steel oven on CF40 flange
Test by making a 3D magneto-optical trap (MOT): preliminary results at first AION workshop (Apr 2019)

Blue fluorescence from atoms in MOT. Estimated cold-atom flux $> 10^9$ s$^{-1}$ (of $^{88}\text{Sr}$)

Stainless steel oven welded to a standard CF40 flange (tested up to 700 °C)

Multichannel nozzle
Strontium atom source

Vacuum region

Oven cross-section

Strontium reservoir

Heater for nozzle
Push laser beam

Probe laser beam

Laser-cooled strontium atoms pushed from a 2D magneto-optical trap (MOT)

Push laser beam

Probe laser beam

Oven temperature = 500 °C

25 Sept 2019
Cold-atom source for strontium:

- ‘Low cost’ – make it ourselves
- Laser system available for AION-10 (need extended warranty)
- Estimated cold-atom flux $> 10^9 \text{ s}^{-1}$ (of $^{88}\text{Sr}$)
Strontium atom source (Singapore)

- Multiple stages: atomic oven, transverse collimator, Zeeman slower, and a deflector (to avoid line of sight to the oven) before collection in a 3D MOT. Length = 1.2m
- Maximum loading rate measured in the MOT: $6 \times 10^9$ atoms/s

Also @NPL
Zeeman slower @ NPL

– Fast atoms cooled by radiative force.
– Scattering rate is velocity-dependent; resonance depends on Doppler shift.
– Zeeman shift induced by a magnetic field (generated by coils or permanent magnets) keeps atoms in resonance with counter-propagating laser.
– High capture velocity (150m/s commonly)

Zeeman slower for strontium based on permanent magnets.
Photos from Stanford lab visit, Jan 2019

Sr source from AOSense Inc.

Sr atoms in blue MOT (large windows)
Sr source from AOSense Inc.

Sr atoms in blue MOT (large windows)
Optics at Stanford

Sr source from AOSense Inc.
Beam-RevC-XX

Cold atomic beam system

- Cold atom flux > 10^{11} atoms/s at T_\perp < 3 mK, axial speed ~40 m/s.
- Miniature chambers (1-2 L) and in-vacuum optics achieve baseline pressures < 10^{-10} Torr.
- Proprietary oven and Zeeman slower, hot window, and integrated transverse cooling/trapping.
- Hot beam flux is entirely blocked from entering the cold beam output port.
- Species available: strontium, calcium, or ytterbium.

Cost > $100 000?
Availability?
Quotation requested

25 cm (approx.)

Florian Schreck et al (Amsterdam): direct transfer from blue to red MOT

First stage of laser cooling by blue light on the strong transition.

Second stage of laser cooling by red light on a narrow transition to very low temperature (weak force)

Red optical molasses for collimation (optional)

Transfer tube

Slowing laser beam with strong intensity gradient

Cloud of Sr atoms at microkelvin temperatures

Blue 2D-MOT

Longitudinal optical molasses beam 1

Longitudinal optical molasses beam 2

Atomic beam of (hot) strontium

Red 3D-MOT

Strontium oven
Another strontium oven (Munich)

From a book of abstracts:

1500 microchannels
Strontium atoms source (2D+ MOT)

– A 2D MOT offers a more compact alternative for ZS.
– Low capture velocity (30m/s vs. 150m/s for ZS) ⇒ efficient oven design.
Strontium atomic energy levels – strong and weak transitions

Laser cooling used to prepare atoms, as well as probing transitions.

Blue transition @ 461 nm
- \( v_{\text{recoil}} = 1.0 \text{ cm s}^{-1} \)
- \( T_{\text{Doppler}} = 770 \, \mu\text{K} \)

Red transition @ 689 nm
- \( v_{\text{recoil}} = 0.7 \text{ cm s}^{-1} \)
- \( T_{\text{Doppler}} \approx T_{\text{recoil}} = 0.2 \, \mu\text{K} \)
### AION-10: Lasers & optics

**Abbreviations:**  
- Ti:Sa – Titanium-doped sapphire laser e.g. M Squared Lasers  
- diode – semiconductor diode lasers, e.g. AO Sense Inc., Toptica

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<tr>
<td>1.</td>
<td>blue cooling (1\textsuperscript{st} stage) – Ti:Sa or amplified diode laser</td>
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<td>2.</td>
<td>red cooling (2\textsuperscript{nd} stage) - diode or Ti:Sa or SFM of fibre lasers</td>
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<td>3.</td>
<td>clock (narrow bandwidth) – power critical for one-photon interferometry</td>
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<td>4.</td>
<td>two repumping lasers – diodes for low power</td>
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<td>5.</td>
<td>dipole trapping lasers – high power at a frequency far off resonance</td>
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<td>– transport by optical tweezers from sidearm into vertical tube</td>
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<td>– optical lattice for launching without heating</td>
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<td>– (Launching squeezed states in future upgrades)</td>
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<td>6.</td>
<td>Optics: mirrors, polarisers, AOMs, EOMs, shutters, optical fibres etc. (modular system for ease of transport to different locations)</td>
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<td>7.</td>
<td>Laser frequency stabilisation – reference cavity provided by National Physical Laboratory (NPL), or a frequency comb (not included in budget)</td>
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To be decided and agreed in the Project Plan:
How much PDRA effort and staff time from AION-Technology/other WPs, will be used to kick start AION-10, e.g. build modules for the laser system?
Laser system, Jason Hogan’s lab@Stanford (Jan 2019)
Strontium atom source

- oven at a temperature over 500°C to give adequate vapour pressure
Optics at Stanford