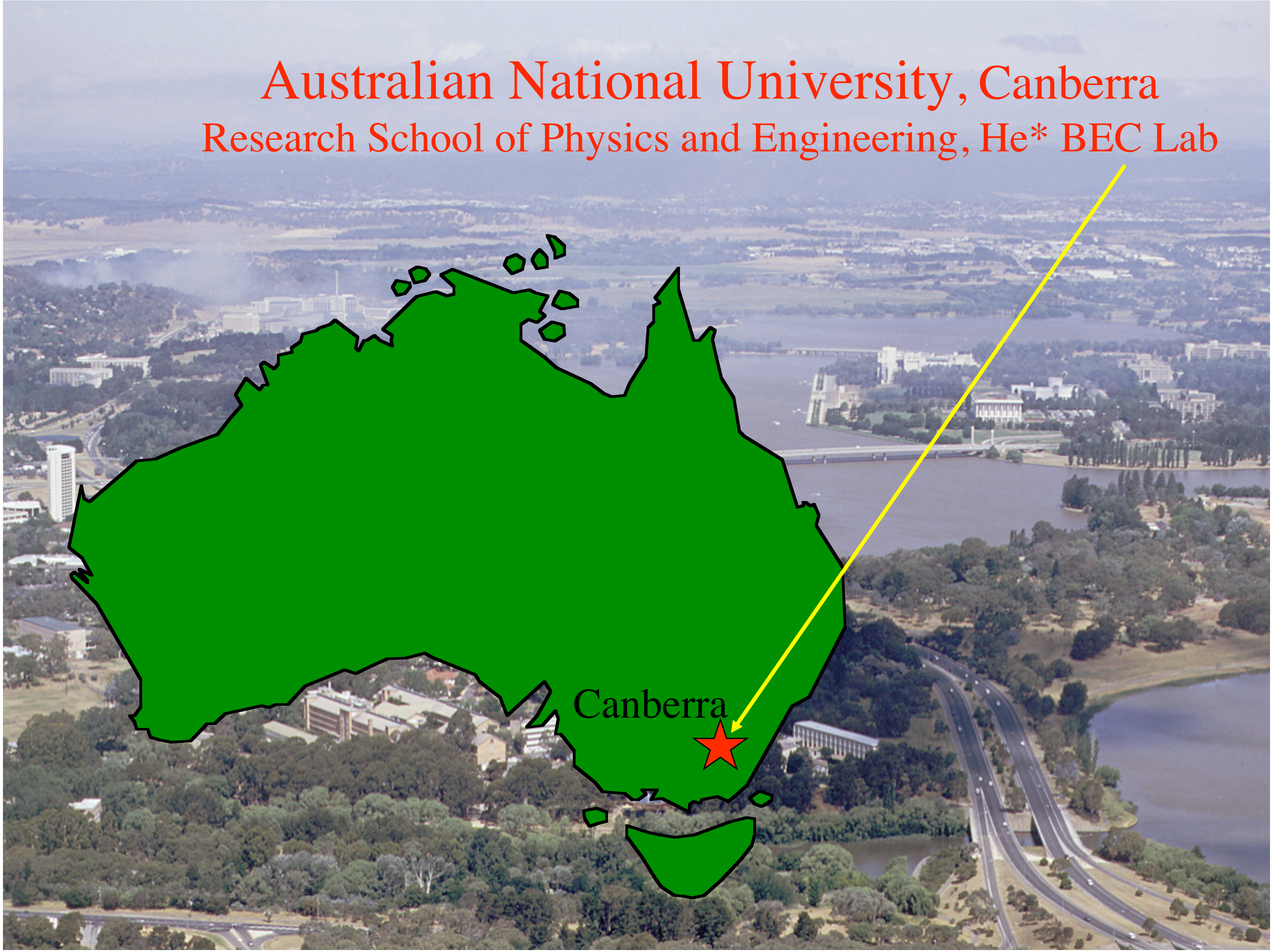
Lecture 1:
Quantum Optics with Atoms: correlations and coherence with ultracold metastable helium

Snowy Mountains, Australia - September 2006


Australian National University, Canberra
Research School of Physics and Engineering, He* BEC Lab
Canberra

Course Outline

LECTURE 1:
Monday June 25th, 2.00 p.m.
ATOM OPTICS WITH METASTABLE HELIUM

LECTURE 2:
Monday June 25th, 3.30 p.m.
METASTABLE HELIUM BEC

LECTURE 3:
Tuesday June 26th, 2.00 p.m.
QUANTUM STATISTICS, COHERENCE AND CORRELATIONS

LECTURE 4:
Tuesday June 26th, 3.30 p.m.
COHERENCE AND CORRELATION EXPERIMENTS AT ANU

Contemporary Physics

Contemporary Physics, Vol. 46, No. 2, March–April 2005, 105–120

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Metastable helium: atom optics with nano-grenades

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In this, the hundredth year since Einstein first postulated the existence of photons, the successful application of wave–particle duality to matter has seen an explosion of activity in the field of atom optics and Bose–Einstein condensation (BEC). This article provides a brief introduction to atom optics, illustrated with applications taken from experiments using helium atoms in long-lived (metastable) excited states. Metastable helium atoms store the greatest amount of energy ($\sim$20 electron volts) in any atomic or molecular system. They behave like nano-hand grenades, making it easy to detect single atoms, opening up promising applications as well as fundamental studies of the quantum statistical properties of atomic systems.

Reviews of Modern Physics

REVIEWS OF MODERN PHYSICS, VOLUME 84, JANUARY–MARCH 2012 p.175

Cold and trapped metastable noble gases

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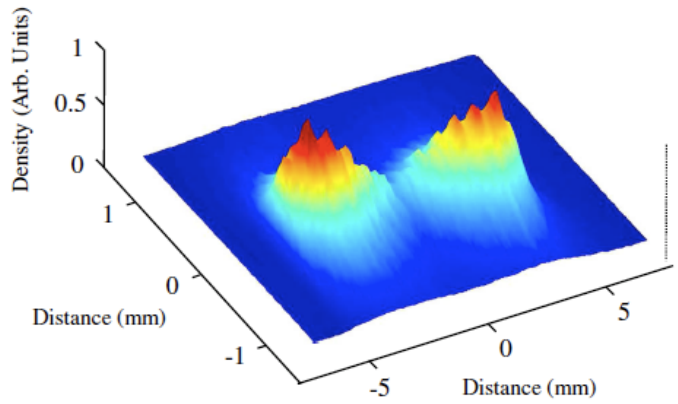
(published 24 February 2012)



Experimental work on cold, trapped metastable noble gases is reviewed. The aspects which distinguish work with these atoms from the large body of work on cold, trapped atoms in general is emphasized. These aspects include detection techniques and collision processes unique to metastable atoms. Several experiments exploiting these unique features in fields including atom optics and statistical physics are described. Precision measurements on these atoms including fine structure splittings, isotope shifts, and atomic lifetimes are also discussed.

DOI: 10.1103/RevModPhys.84.175 PACS numbers: 03.75.−b, 67.85.−d, 34.50.−s, 32.30.−r

Lecture 1 Outline

LECTURE 1: ATOM OPTICS WITH METASTABLE HELIUM (He*)

- The unique properties of He* which yield special capabilities for atom optics

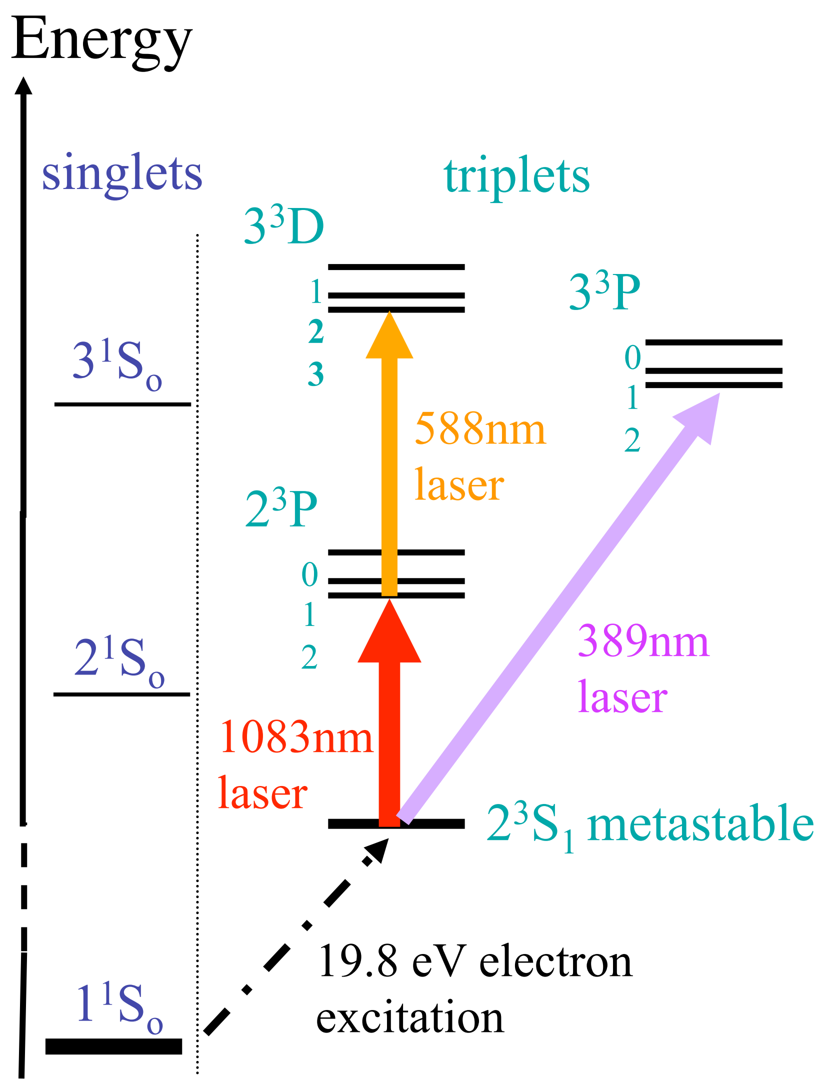
- Creating a controlled source of He*

- Applications to atom optics
  - Atom lithography
  - Guiding atoms in hollow optical fibres

- Applications to atomic physics
  - Electron-He* collisions
  - Metastable state lifetime measurements

Metastable Helium Properties

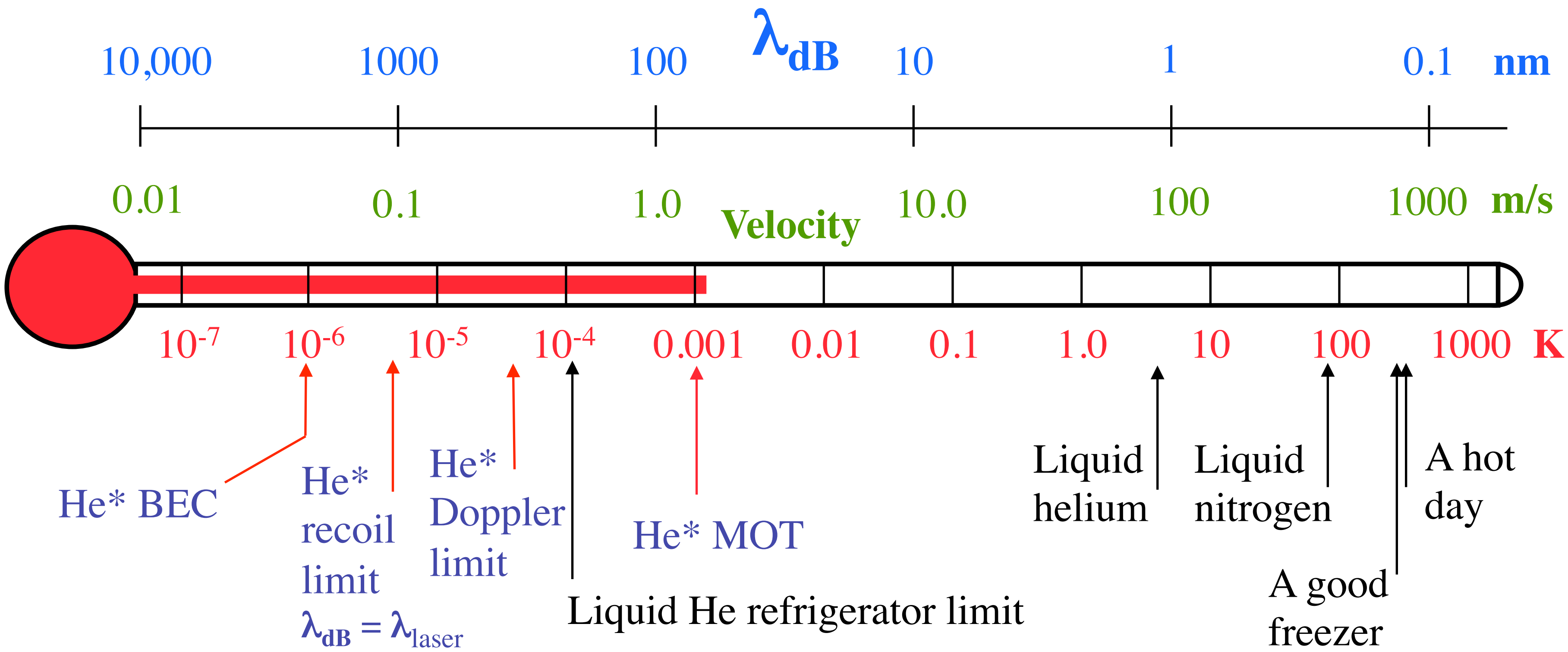
- He* is an important energy pool in astrophysical, atmospheric and plasma physics because of its
  - long 2^3S_1 lifetime ~ 8000s
    - spin flip and ΔL forbidden
    - longest lived metastable
  - ~ 20 eV stored energy
    - easy to detect single atoms
    - MCP, EM, metal plate ~70%
  - large ~ 100's nm^2 x-sections
    - long range potentials
- We excite He* atoms to the 2^3S_1 metastable state in an electric discharge
  - effectively a ground state atom
- Transitions at 1083 (389) nm
  - diode, fibre and frequency doubled lasers to cool and trap



Atom Optics Properties

Atom	Transition	λ (nm)	τ (ns)	Doppler T_d (μK)	Doppler V_d (cm/s)	Recoil T_r (μK)	Recoil V_r (cm/s)	I_s(mW/cm^2)
H	$1^2S_{1/2} \rightarrow 2^2P_{3/2}$	121.567	1.6	2387	444	1286	326	7237
He*	$\mathbf{2^3S_1 \rightarrow 2^3P_2}$	**1083.034**	**98.04**	**38.96**	**28.44**	**4.08**	**9.20**	**0.167**
	$\mathbf{2^3S_1 \rightarrow 3^3P_2}$	**388.865**	**106.83**	**35.75**	**27.25**	**31.6**	**25.6**	**3.31**
Ne*	$3s[3/2]_2 \rightarrow 3p[5/2]_3$	640.225	19.5	196	28.4	2.32	3.09	4.07
Ar*	$4s[3/2]_2 \rightarrow 4p[5/2]_3$	811.531	30.2	126	16.2	0.73	1.23	1.29
Kr*	$5s[3/2]_2 \rightarrow 5p[5/2]_3$	811.29	28	136	11.6	0.35	0.59	1.40
Xe*	$6s[3/2]_2 \rightarrow 6p[5/2]_3$	881.941	34	112	8.4	0.188	0.34	0.89
Li	$2^2S_{1/2} \rightarrow 2^2P_{3/2}$	670.778	27.1	141	41.1	6.1	8.57	2.54
Na	$3^2S_{1/2} \rightarrow 3^2P_{3/2}$	588.995	16.2	236	29.2	2.40	2.95	6.28
K	$4^2S_{1/2} \rightarrow 4^2P_{3/2}$	766.49	26.4	145	17.5	0.83	1.33	1.75
Rb	$5^2S_{1/2} \rightarrow 5^2P_{3/2}$	780.027	27	141	11.7	0.37	0.60	1.62
Cs	$6^2S_{1/2} \rightarrow 6^2P_{3/2}$	852.113	30.52	125	8.8	0.20	0.35	1.10
Mg	$3^1S_0 \rightarrow 3^1P_1$	285.213	2.0	1910	81	9.7	5.8	448
Ca	$4^1S_0 \rightarrow 4^1P_1$	422.673	4.5	849	42	2.7	2.36	61.2
Sr	$5^1S_0 \rightarrow 5^1P_1$	460.733	4.98	767	27	1.03	0.99	42.7
Cr	$4a^7S_3 \rightarrow 4z^7P_4$	425.331	31.8	120	13.9	2.04	1.80	8.50

He* Temperatures



Some important numbers for He*

$V_r = hk / m$ ~ 9 cm/s at 1083 nm
~ 26 cm/s at 389 nm

$A_{max} = hk / 2m\tau$ ~ 4.7×10^5 m/s^2 at 1083 nm
(τ ~ 100ns) ~ 1.3×10^6 m/s^2 at 389 nm

To slow He* atoms from 1000m/s (LN_2 cooled source)

$T_{min} = 1000 / A_{max}$ ~ 2 msec at 1083 nm
~ 0.8 msec at 389 nm

D_{min} ~ 1 m at 1083 nm
~ 0.4 m at 389 nm

$T_r = (hk)^2 / mk_B$ ~ 4 mK at 1083 nm
~ 32 mK at 389 nm

He* : Pros

- ✓ Large stored energy - 20eV
  - ✓ exposures for atom lithography
  - ✓ EASY DETECTION - single He*
  - ✓ de-excite: low background
- ✓ No nuclear spin for ^{4}He*
  - ✓ Simple energy structure
  - ✓ No repumping needed
- ✓ Big recoil velocity 9 (26) cm/s
  - ✓ Make good beamsplitters
- ✓ Low sat. int. 0.17 (3.3) mW/cm^2
  - ✓ Low power (diode) lasers
- ✓ Large magnetic moment $2\mu_B$
  - ✓ Easier magnetic control
- ✓ Large scattering length a = +7.512 nm
  - ✓ Efficient evaporation
  - ✓ ^{3}He* - ^{4}He* a is larger ~ + 30 nm

He* : Cons

- ✓ Large stored energy 20eV
  - ✗ Penning ionization losses
  - ✗ Low number densities
  - ✓ BUT drops by >10^4 in B field
- ✓ Nuclear spin for ^{3}He*
  - ✗ ^{3}He* repumper needed
- ✓ Big recoil velocity 9 (26) cm/s
  - ✗ High recoil temperature
- ✓ Hard to make
  - ✗ Low numbers
  - ✗ Complex apparatus

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He* Production

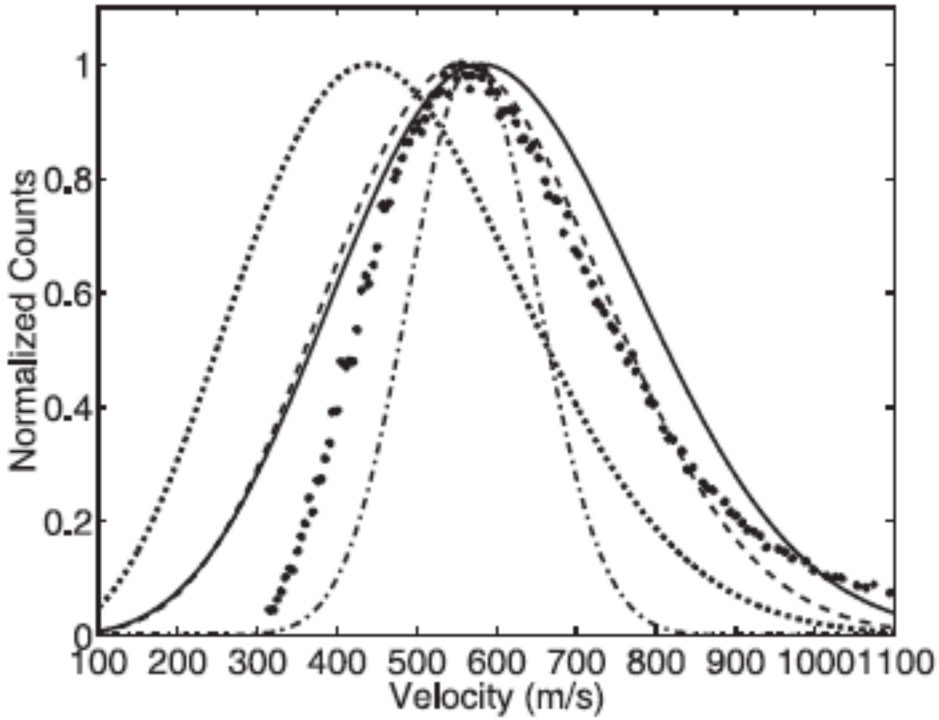
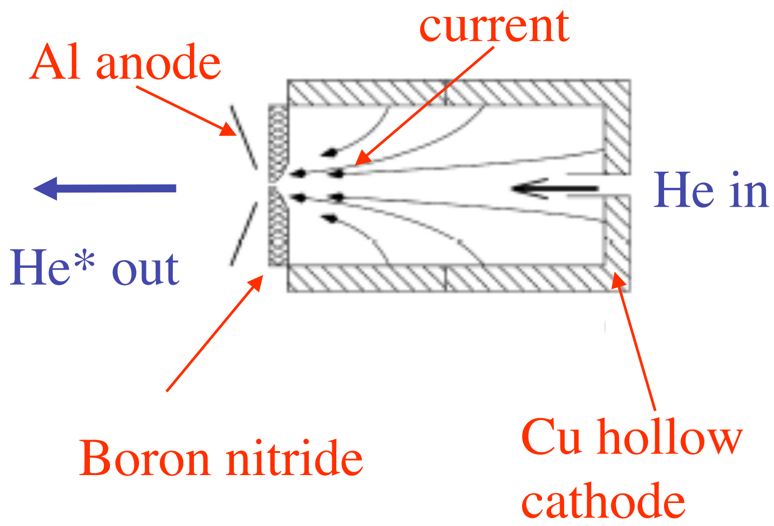


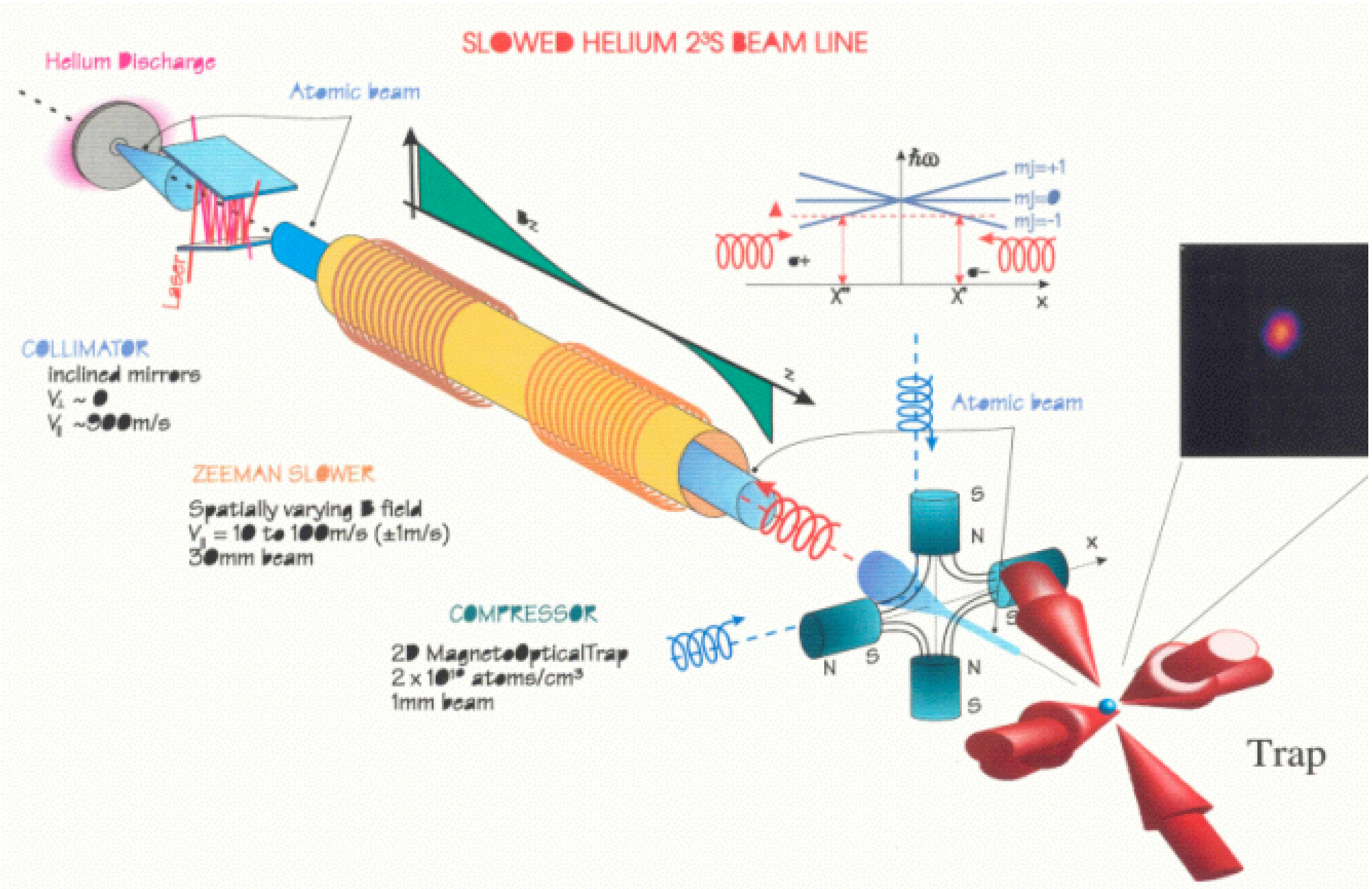
FIGURE 1 Effusive (*dotted*) and supersonic ($M = 1$, *dashes*; $M = 3$, *solid*; $M = 5$, *dash-dot*) velocity distributions for a source temperature of ~ 25 K as a function of Mach number. The data points are taken using the final version of the hollow cathode at a pressure of 0.36 Torr and 400 volts

Swansson et al., Applied Physics B **79**, 485 (2004)

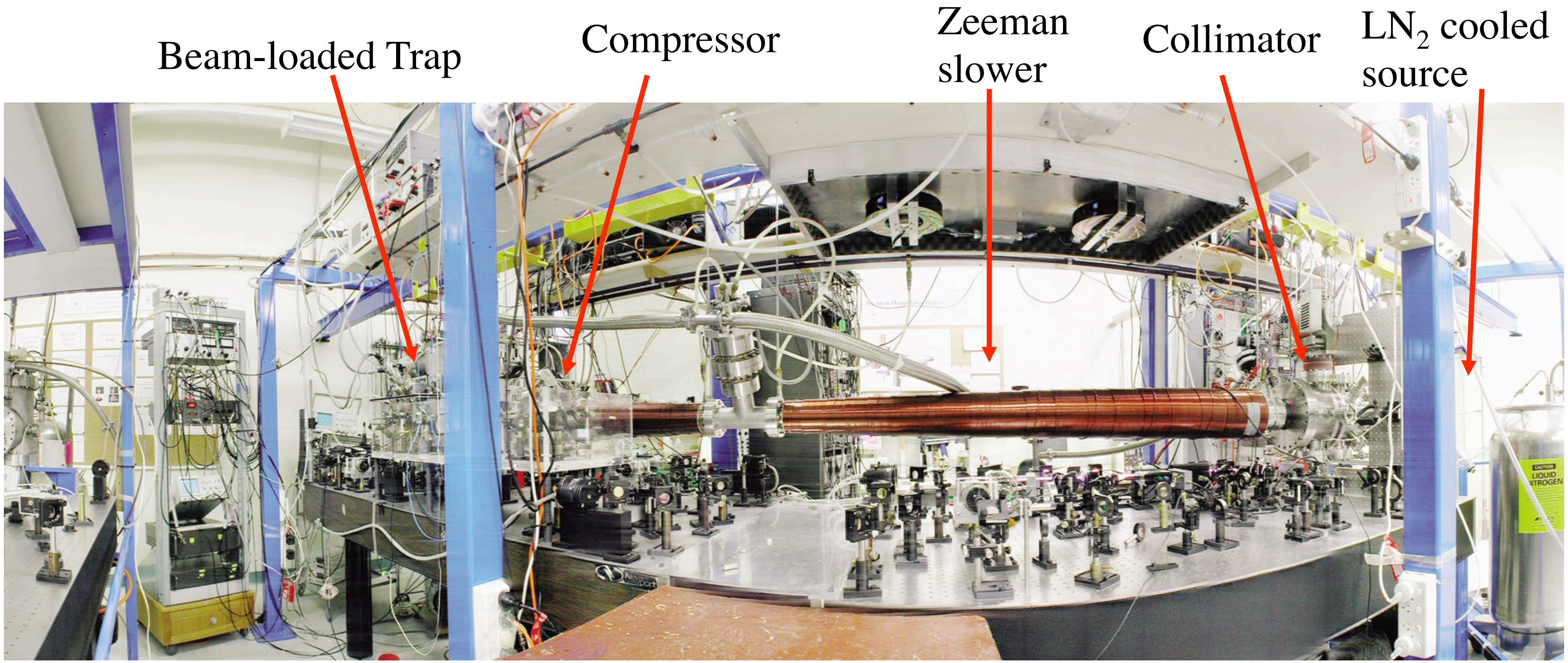


- Efficiency very low ~ 10^{-4} - 10^{-5} probability of excitation to 2^3S_1 state
- Use external anode and large area hollow cathode to maximise He*
- Cool to LN_2 or LHe temperatures to reduce longitudinal velocity
- Velocity near effusive ~ M = 1
- Flux ~ 10^{14} - 10^{15} He*/s/ster

Creating a bright beam



Bright He* Beam Machine



Flux	**~ 3 x 10^{10} He*/s**
Velocity	**~ 50 - 100 m/s**
Area	**~ 2 mm^2**
Divergence	**~ 10 mrad**

- Brightness increased over the original source
- Trap density 5x10^9 cm^{-3} is >100 times that near source

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He* atom Lithography

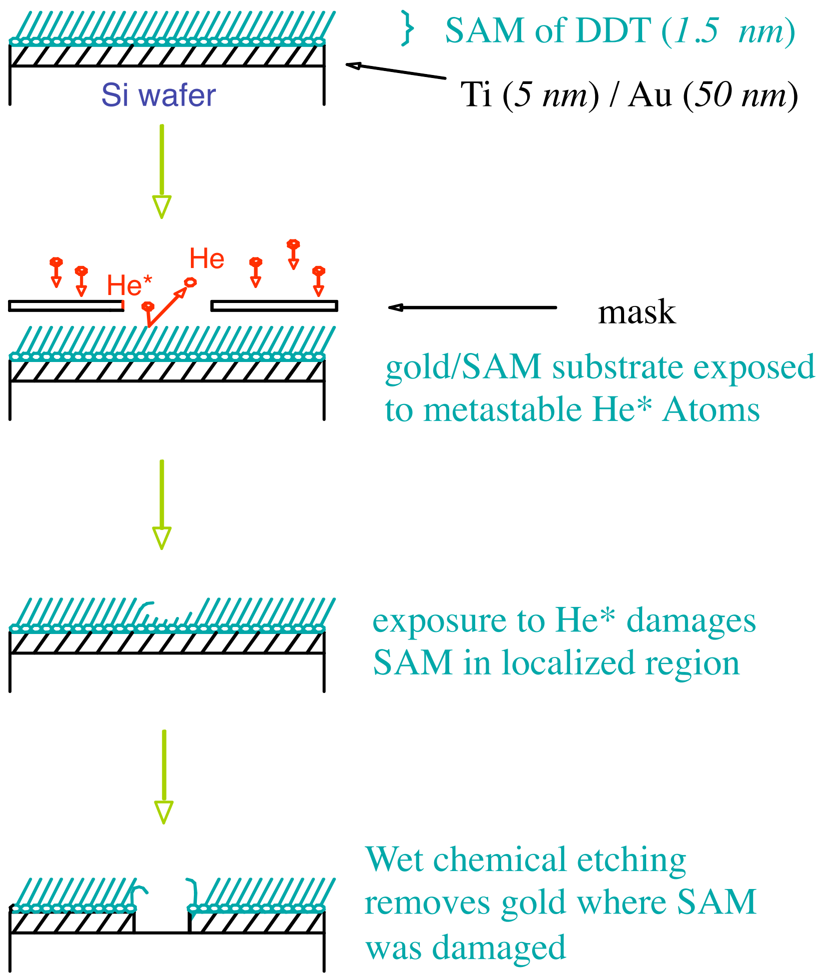
Photoresist - a Self-Assembled Monolayer (SAM) of DDT (dodecanethiole) molecules:

- 1.5nm DDT - $CH_3(CH_2)_{11}SH$
- 50nm Au / 5nm Ti coating
- Si wafer substrate

SAM bond energies << 10 eV *c.f.* He* energy ~ *20 eV*

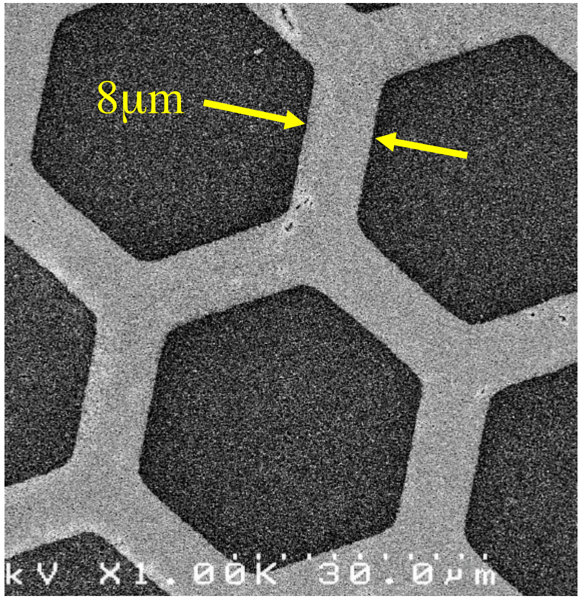
SAM dosage

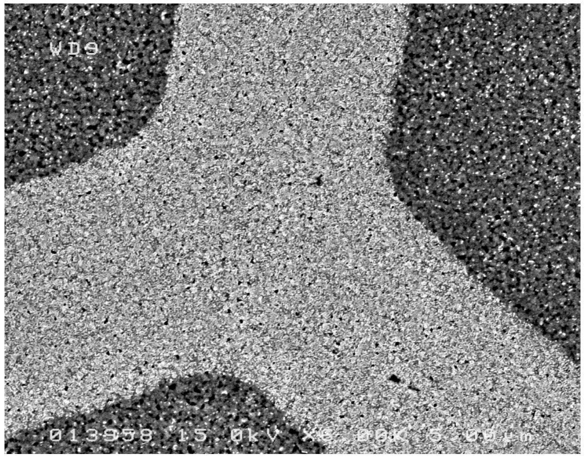
- SAM footprint ~ 0.1 nm^2
- dosage > *0.5* He* / molecule
- exposure time *10 - 60* mins *~33cm* from the He* source



Atom Lithography Results

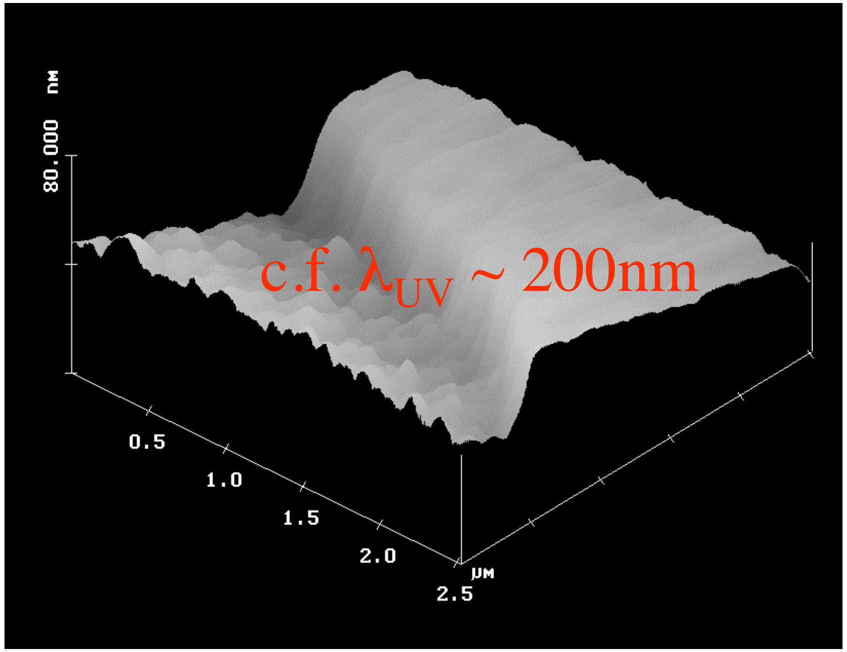
W. Lu, K.G.H. Baldwin, M.D. Hoogerland, S.J. Buckman, T.J. Senden, T.E. Sheridan and R.W. Boswell, *J. Vac. Sci. Technol.* **16**, 3846 (1998)



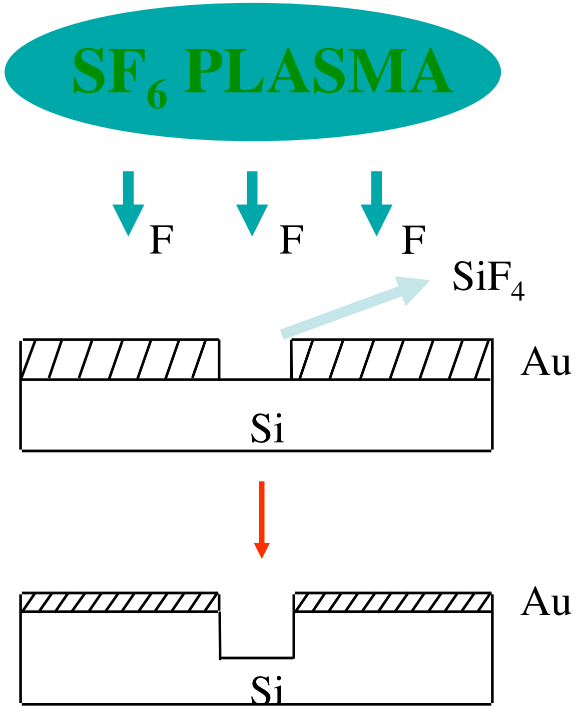


SEM images of gold pattern on Si using 8 μm wide hexagonal grid mask.

AFM images of edge structure:
30nm edge resolution ~ Au depth

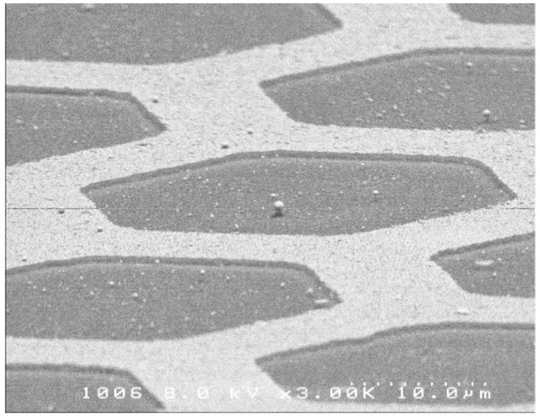


Plasma etch in Si

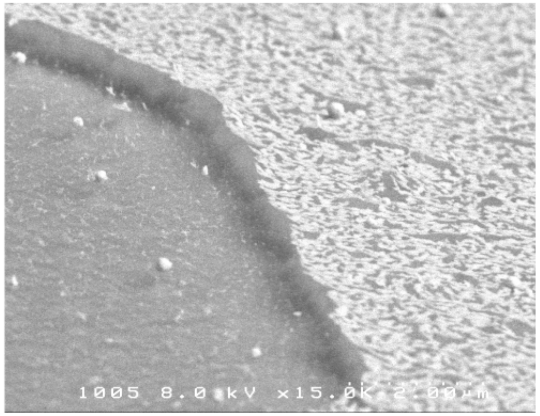


Plasma processing in fluorine (SF_6) selectively etches Si faster than Au

SEM images of hexagonal grid pattern plasma-etched into Si to form a series of well structures.

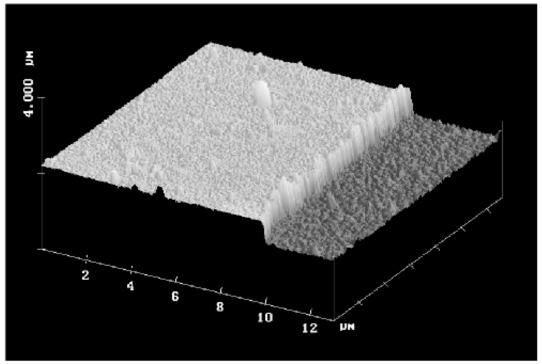


a



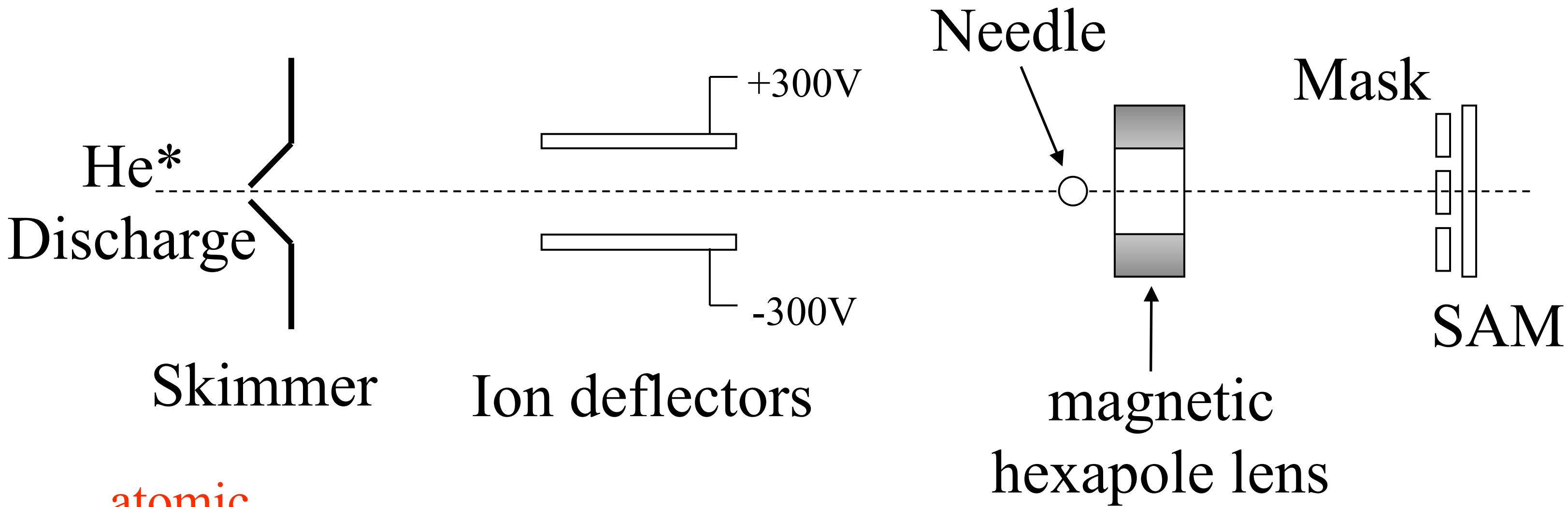
b

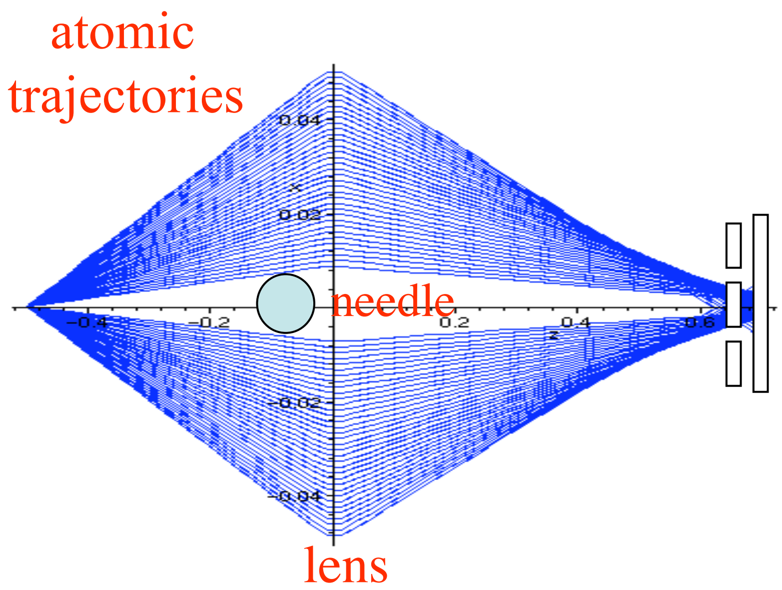
AFM image of plasma-etched Si structures showing 580nm well depth. The edge height-to-width ratio is > 14.

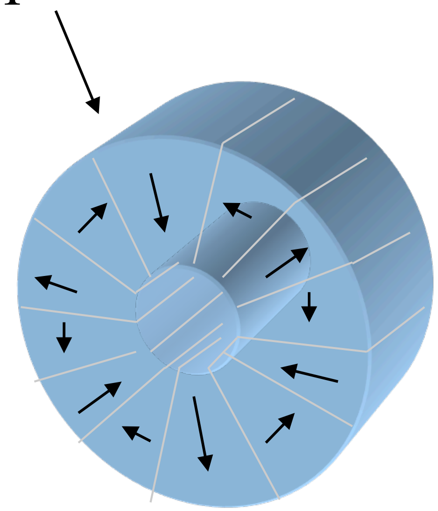


c

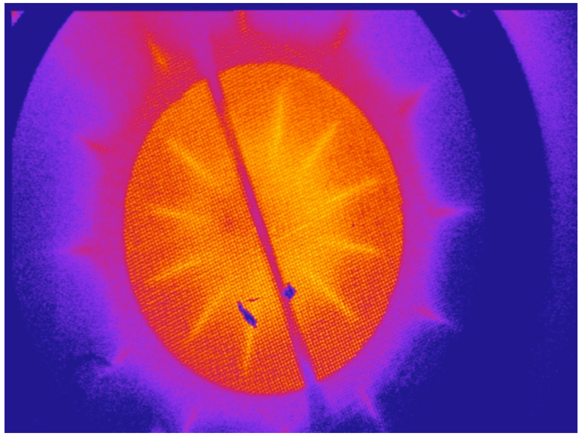
UV-free He* Lithography



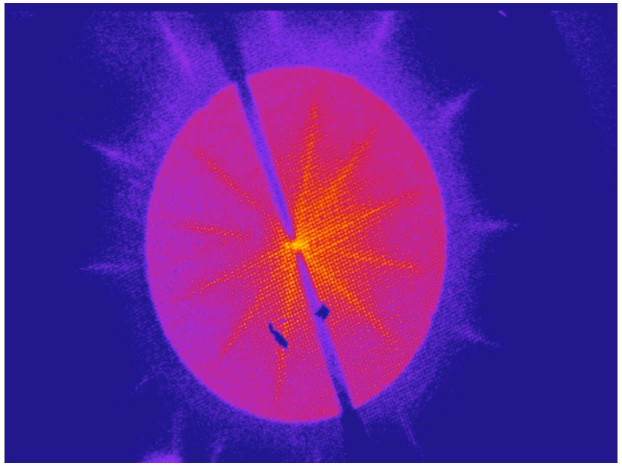




He* focusing results

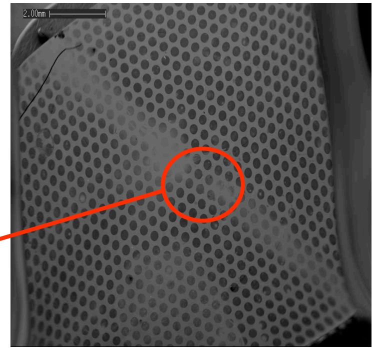


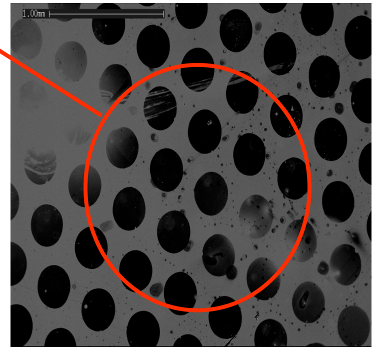
High velocity beam - weak focus

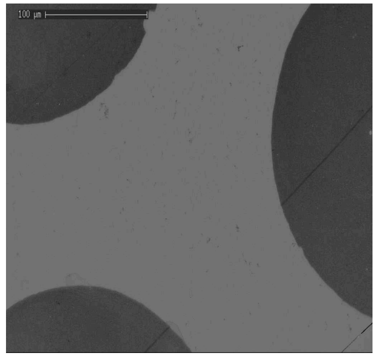


Low velocity beam - tight focus in shadow

Exposure in needle shadow

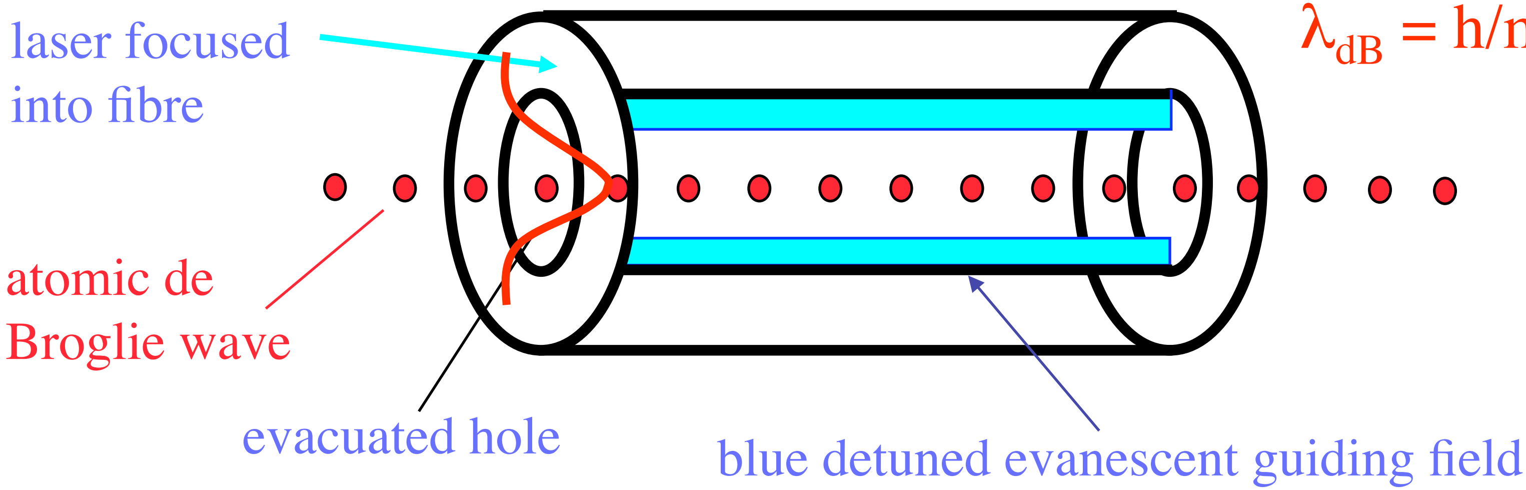






R.R. Chaustowski, V.Y.F. Leung and K.G.H. Baldwin, *Applied Physics B* 86 (3), 491-496 (2007)

Hollow Optical Fibre Atom Guide

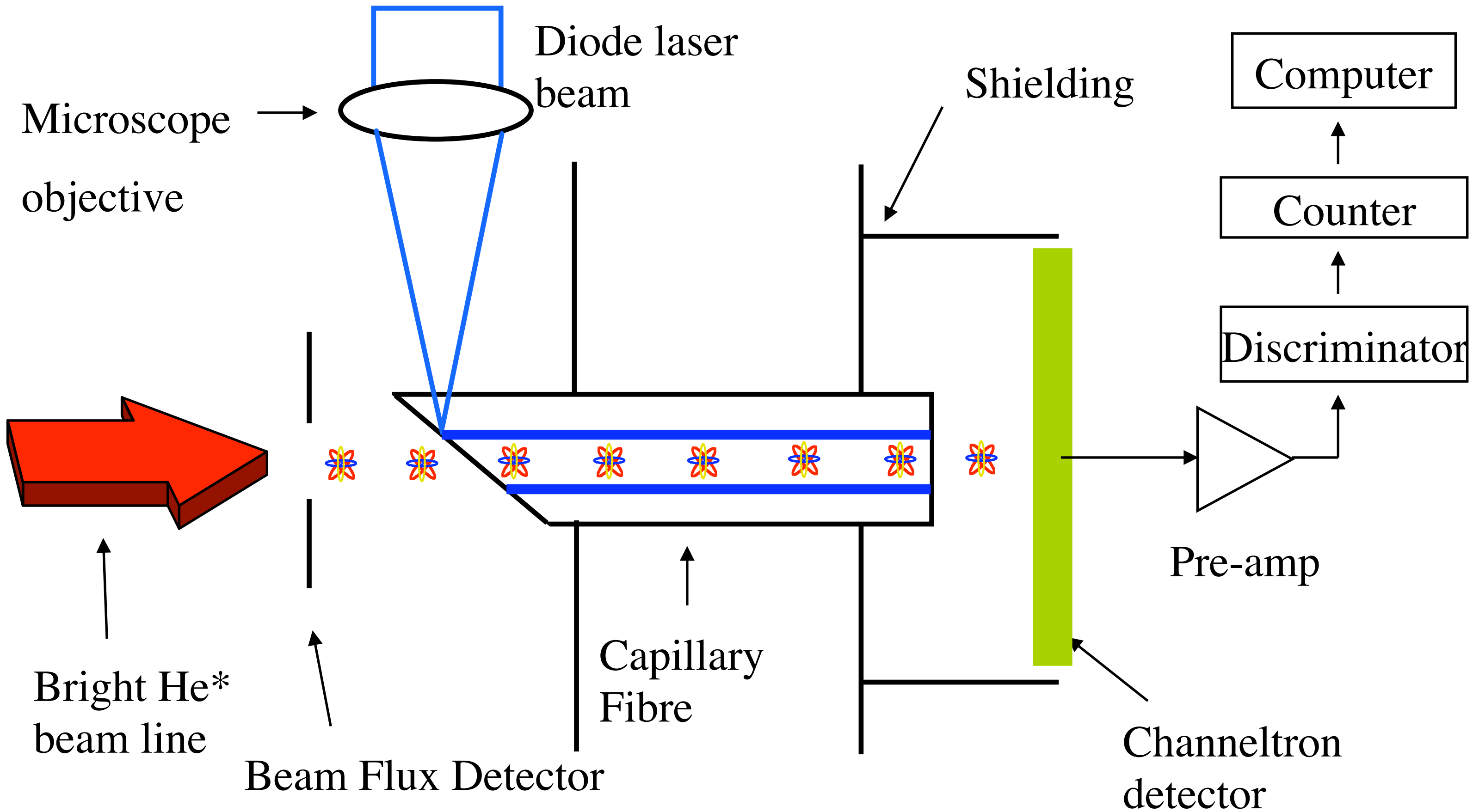


$\lambda_{dB} = h/mv$

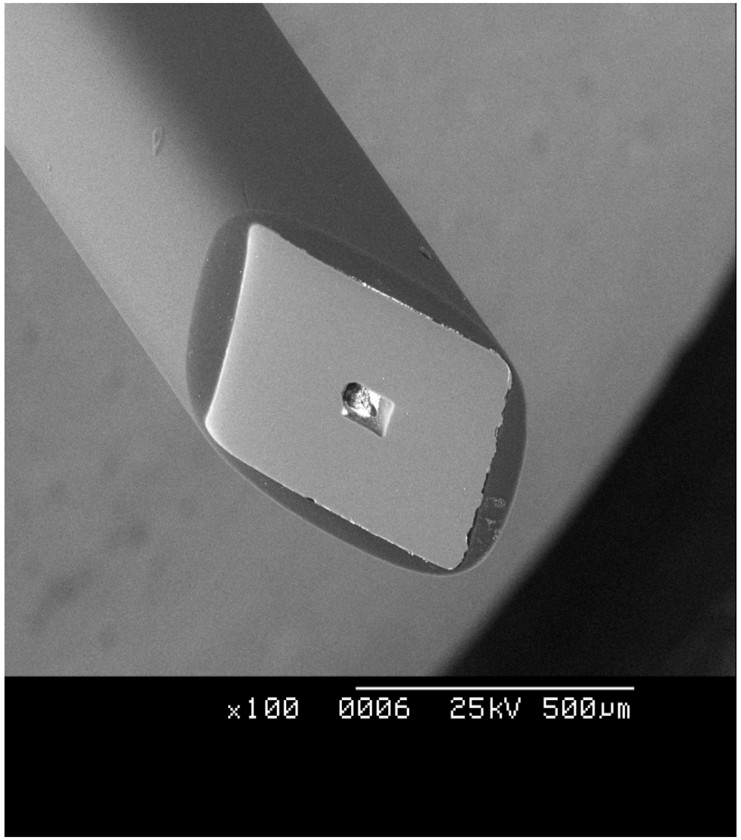
- Atoms are kept away from the hollow fibre wall by the dipole force interaction with the blue-detuned evanescent guiding laser field
  - When λ_{dB} << hollow core diameter => a hose for atoms
  - When λ_{dB} ~ hollow core diameter => atom guiding
  - For a 1 μm hollow core diameter => 0.1 m/s helium atoms i.e. recoil limited cooling

- Applications: atomic micro-delivery; atom interferometry with large enclosed area; and out-of-vacuum atom transmission.

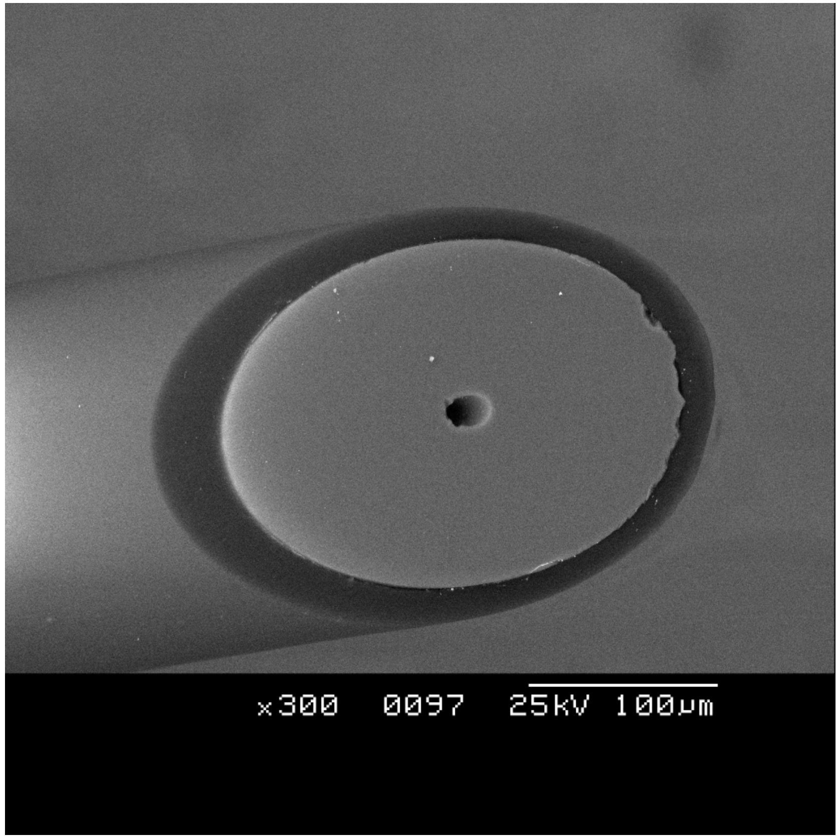
Hollow Fibre Experiment



Hollow optical fibres

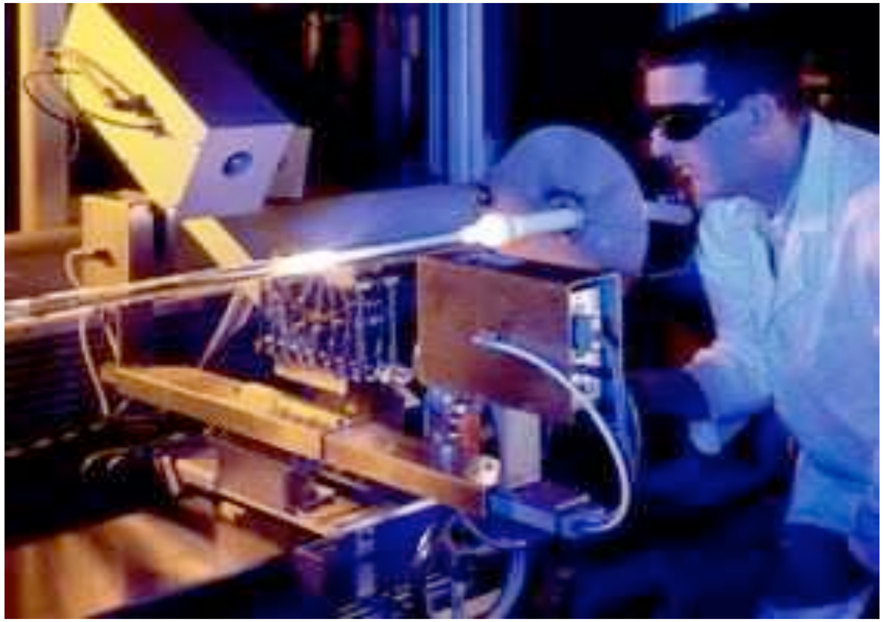


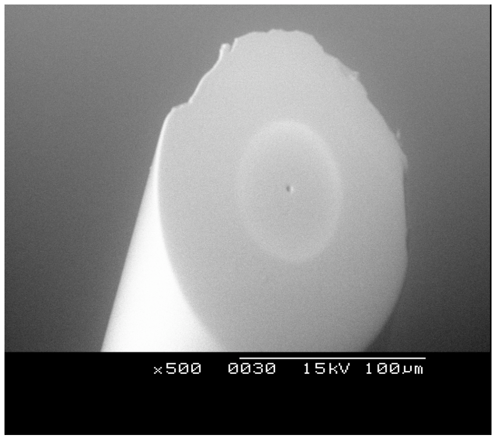
SEM image of square capillary:
350µm diameter wide
50µm diameter hole



SEM image of round capillary:
150µm diameter wide
10µm diameter hole

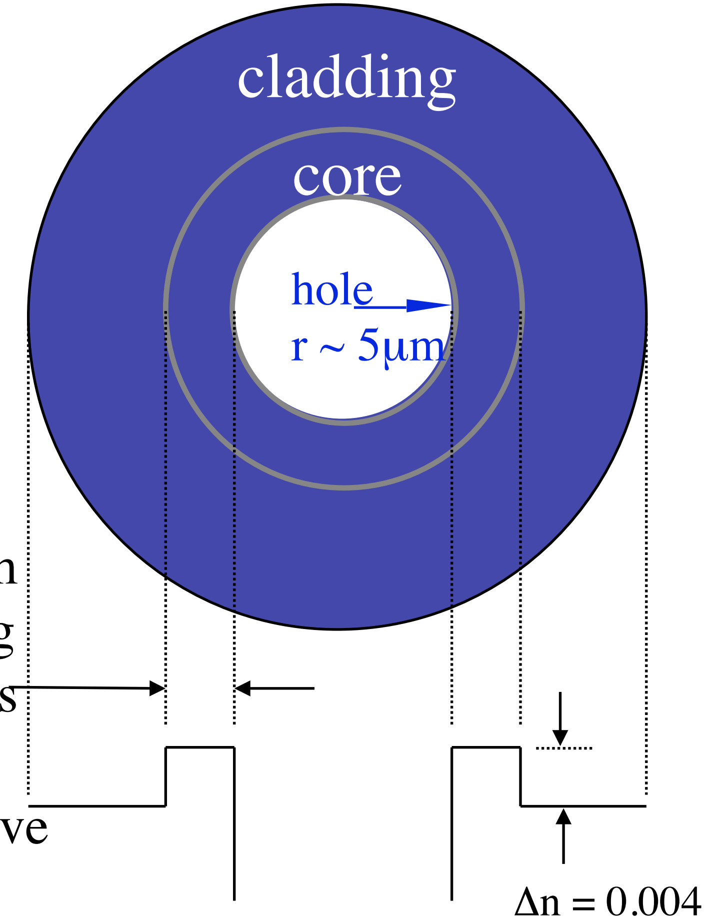
Single light mode HOF





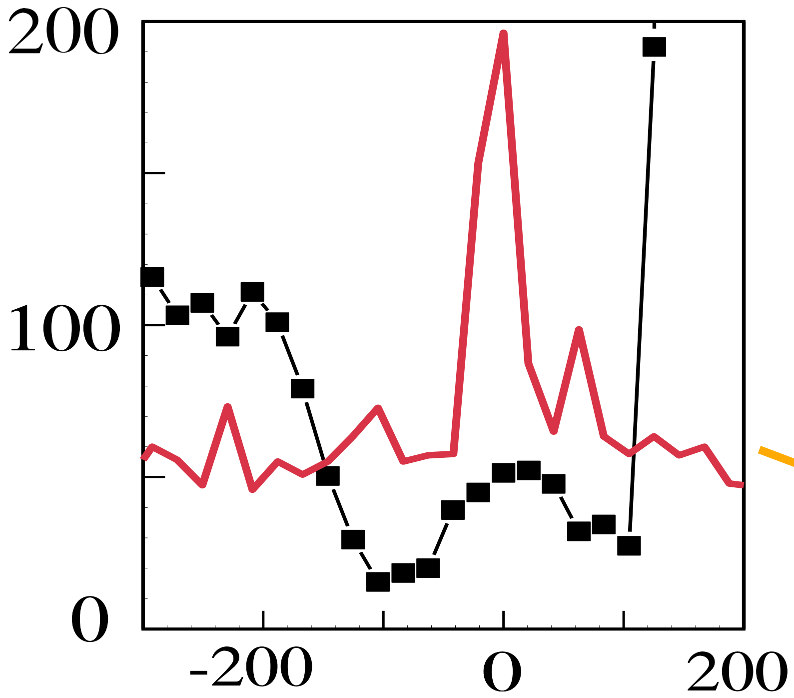
Fibre fabricated at Optical Fibre Technology Centre, Sydney

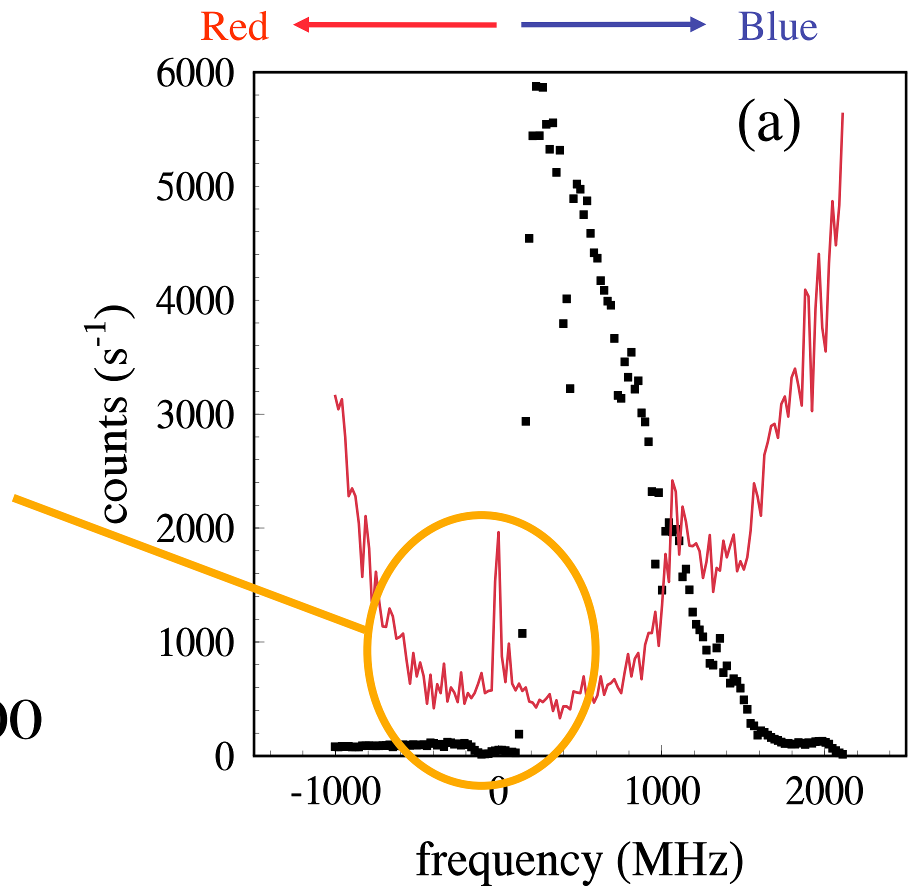
few µm guiding annulus



refractive index profile

Hollow Fibre Guiding Results





Detail near zero detuning showing loss of atoms from ballistic flux due to red-detuning attraction to fibre wall

Red line: saturated absorption signal
Black dots: transmitted He* counts

R.G. Dall, M.D. Hoogerland, K.G.H. Baldwin and S.J. Buckman, *J. Optics B* **1**, 396 (1999)

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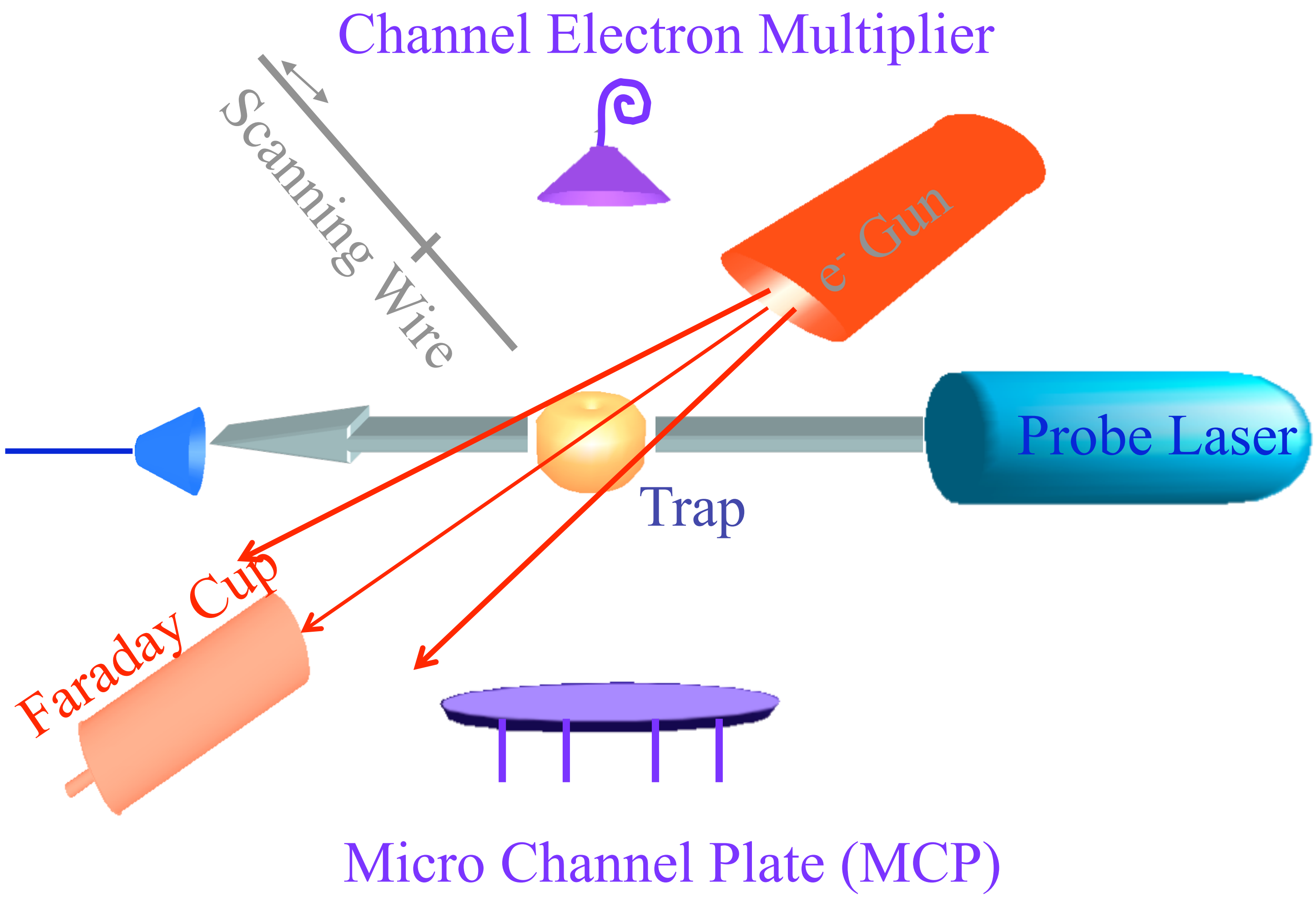
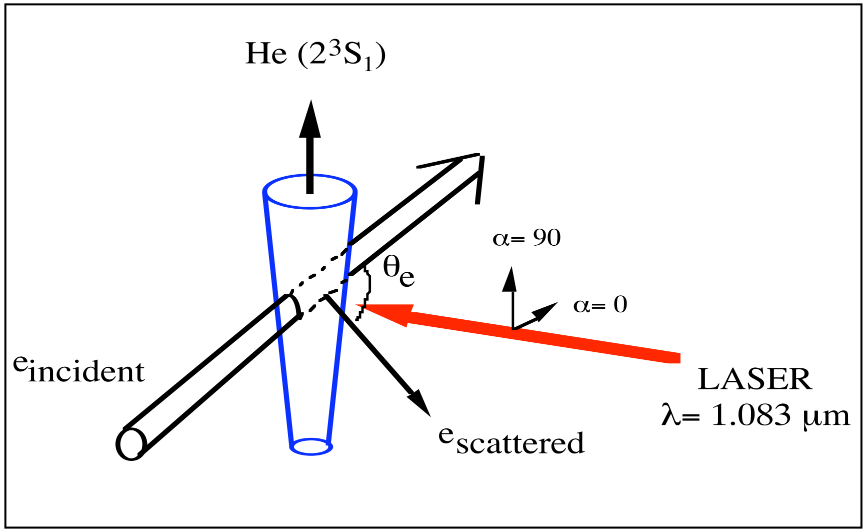
e$^-$ - He* Collisions



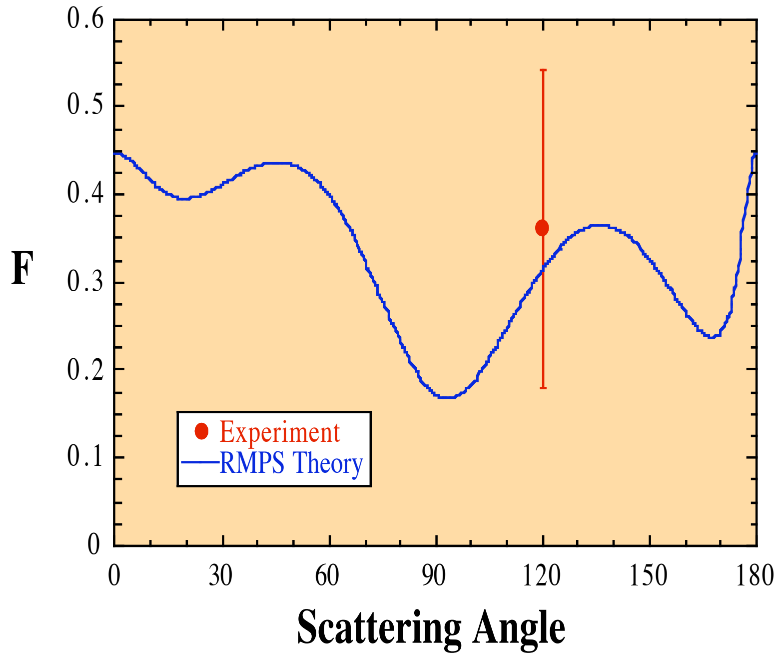
Conventional e^- - He* scattering



In *Jacka et al., J.Phys. B 29, L825 (1996)* we measured the polarisation ratio

$$F = \frac{I(0°) - I(90°)}{I(0°) + I(90°)}$$

for electrons scattered from a laser-polarised He* beam



Conventional He* Source

- n < 5 x 10^7 cm^{-3} near He* nozzle
- count rate < 0.1 Hz < background
- 3 WEEKS to acquire one data point!

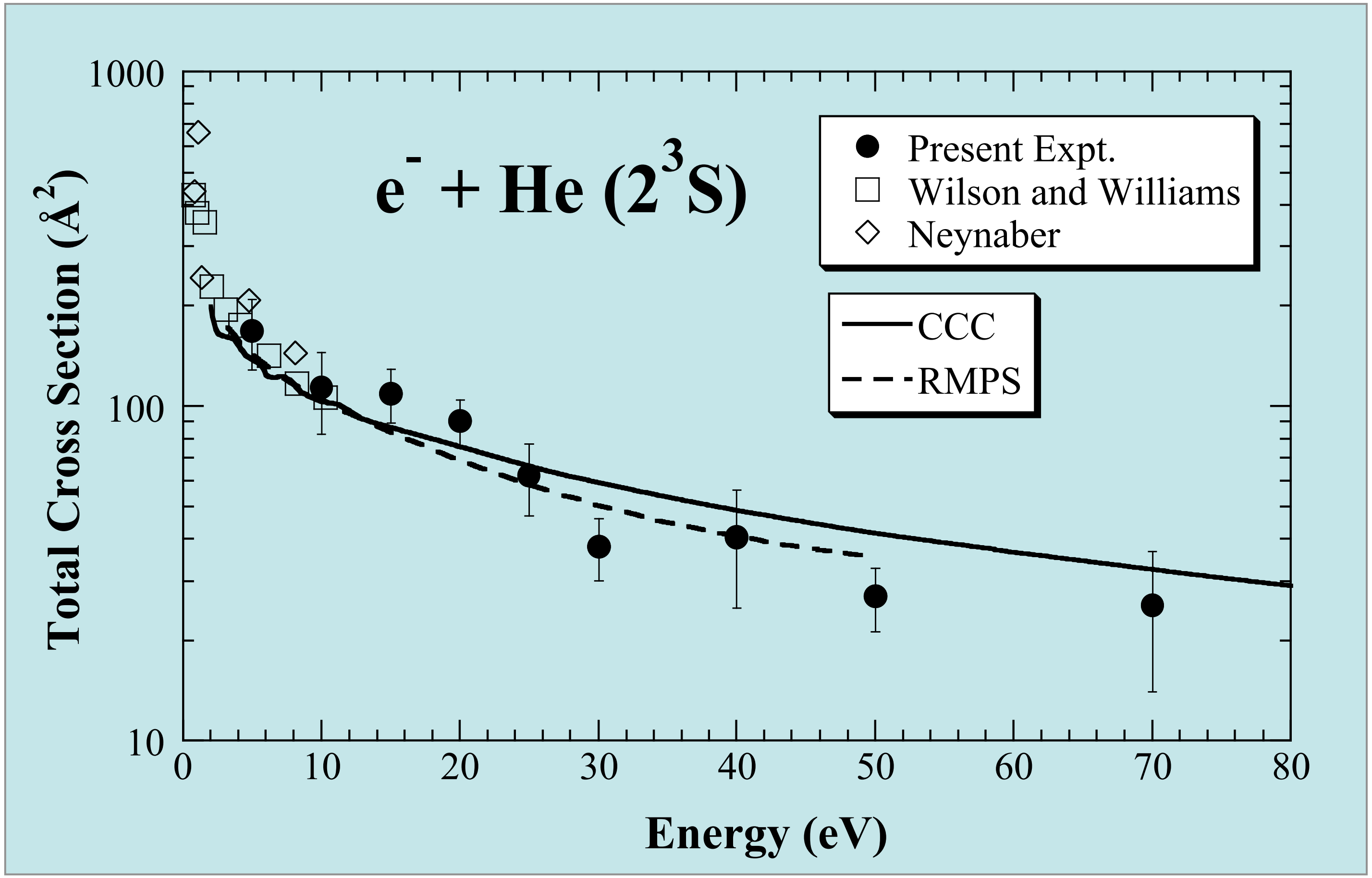
Atom trap

- n ~ 5 x 10^9 cm^{-3}
- HOURS of data acquisition time

He* - e$^-$ Collision Results

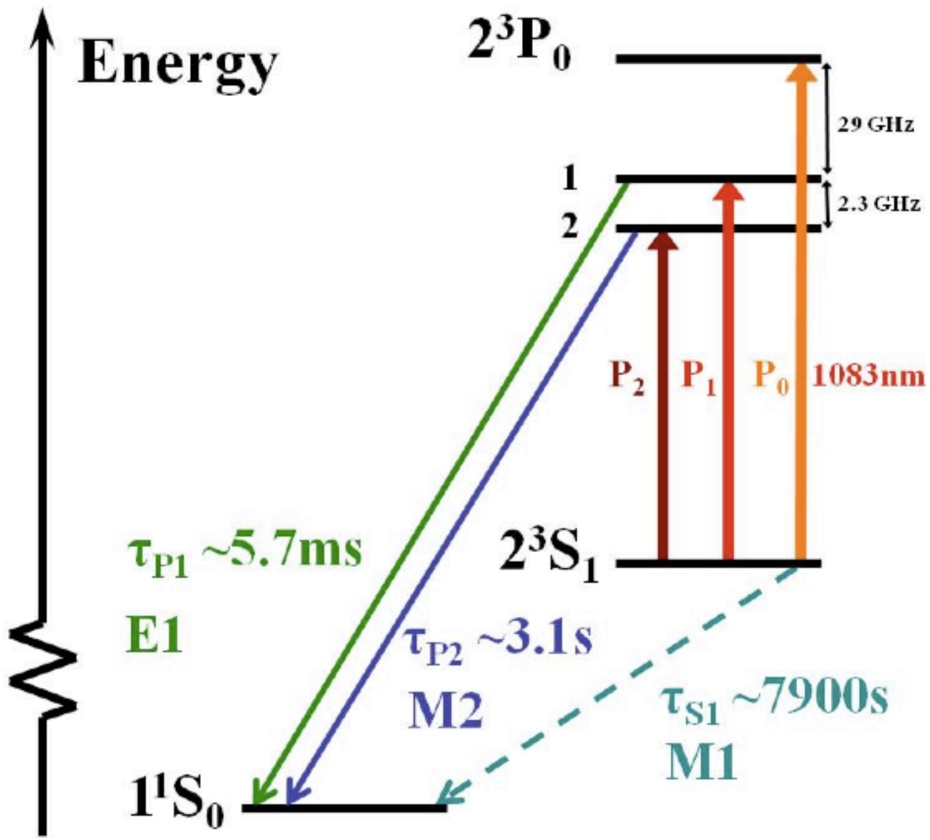
- First measurement of He*-e$^-$ total cross sections at energies above 10eV
- Good agreement with CCC and RMPS theoretical calculations

L.J. Uhlmann, R. Dall, A.G. Truscott, M.D. Hoogerland, K.G.H. Baldwin and S.J. Buckman, *Physical Review Letters* **94**, 173201 (2005)



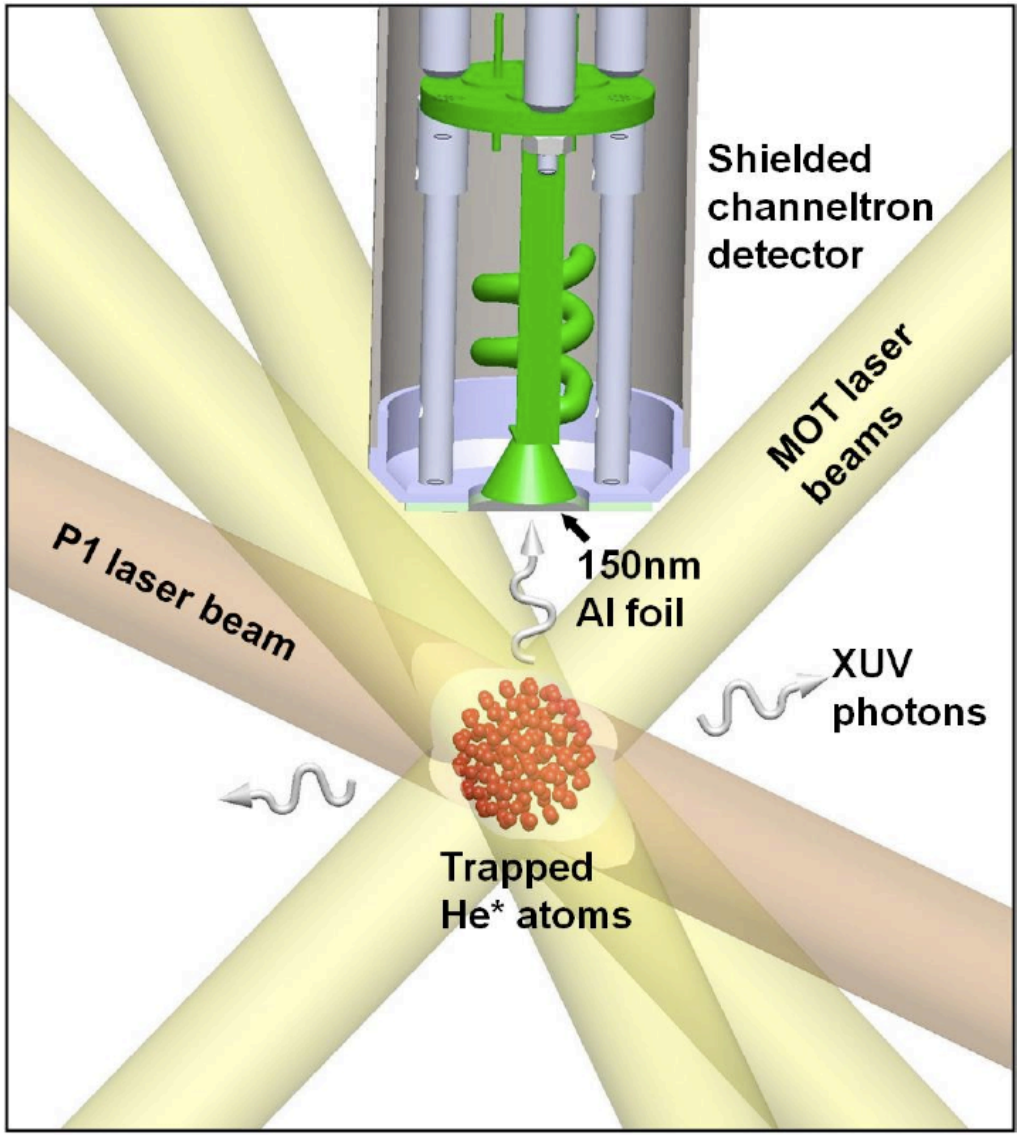
The Helium triplet manifold

- A QED testbed: the fine structure splitting of the 2^3P manifold shows a significant discrepancy with QED theory – *yet to be resolved !*
- Decay rates from the 2^3P manifold yet to be measured
  - 2^3P_2 – M2 transition (~5.7ms)
  - 2^3P_1 – E1 transition (~3.1s)
  - 2^3P_0 – strictly forbidden
- He 2^3S_1 is the longest lived neutral atomic excited state yet measured (once before):
  - Moos and Woodworth (1975) ~9000 ± 3000s - M1 transition

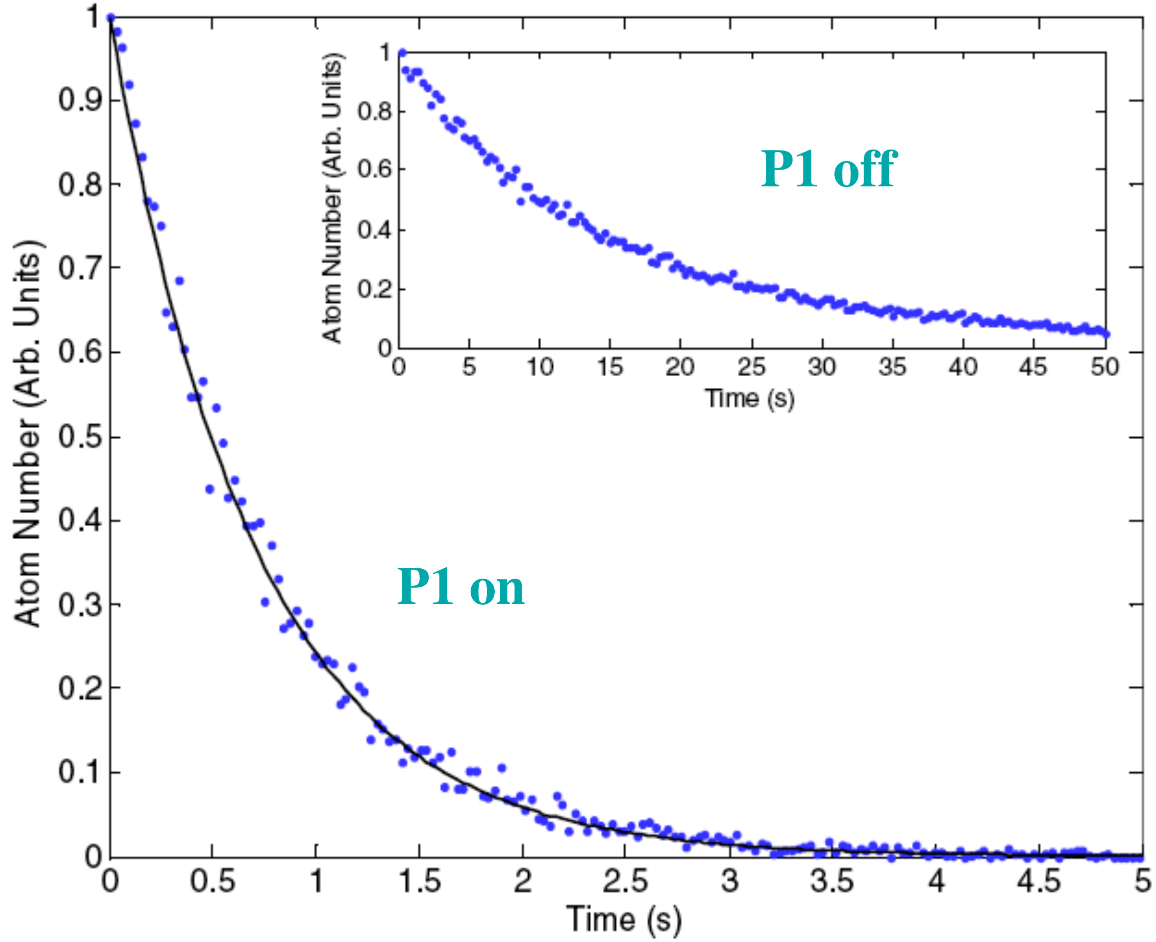


Lifetime Decay Experiments

- First measure 2^3P_1 decay via direct loss rate from cold atomic ensemble
- Then measure the XUV photon flux from the 2^3P_1 state to the ground state
- Use to calibrate the XUV flux (decay rate) for the
  - 2^3P_2 – M2 transition
  - 2^3P_0 – strictly forbidden
- and the metastable state
  - 2^3S_1 – M1 transition



$2^3P_1 - 1^1S_0$ decay measurements



2^3P_1 - 1^1S_0 decay: a test of QED

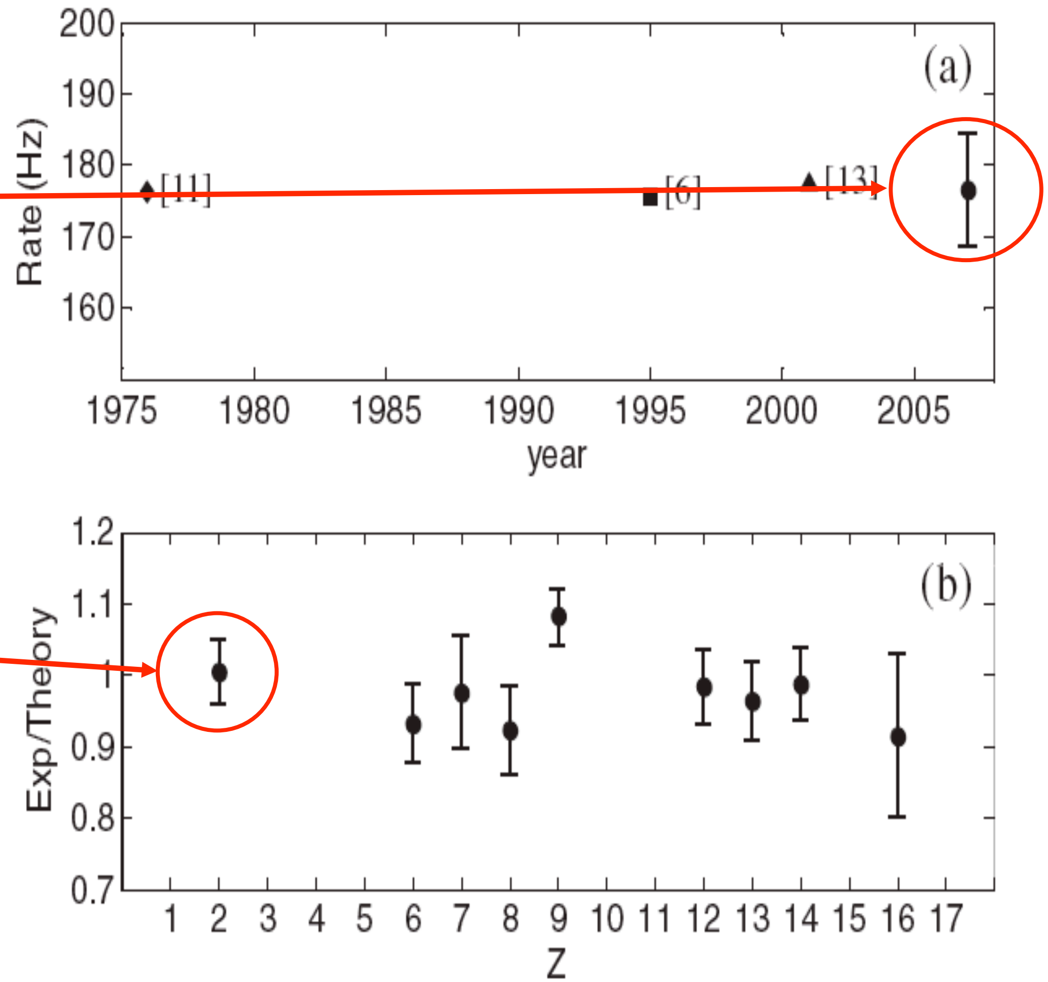
Dall et al., *Phys. Rev. Lett.* **100**, 023001 (2008)

- Consensus of predicted decay time ~ 5.67 s

- First measurement of decay time = 5.66 (25) s

- The value for He anchors the 2^3P_2 - 1^1S_0 isoelectronic sequence

- Uncertainty is less than others in the sequence

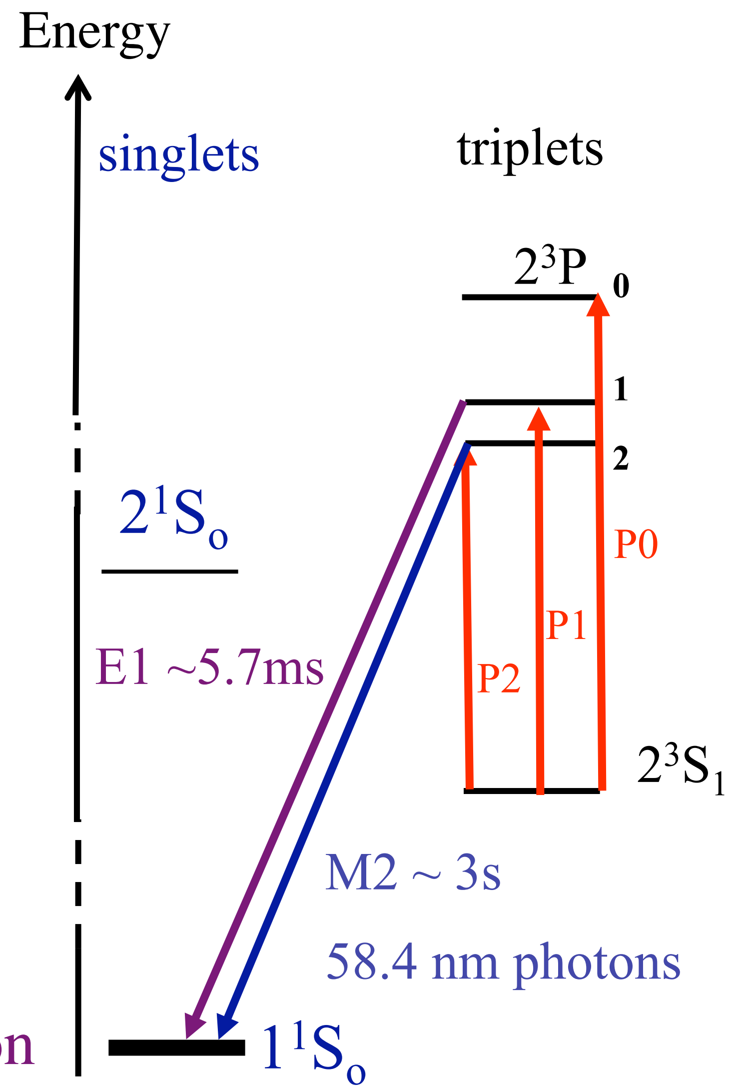


He 2^3P manifold: 2^3P_2, 2^3P_0 decay

- The 2^3P manifold decays to the ground state via radiation at ~ 58.4 nm (~20eV)

- Theory predicts the following decay times:
  - 2^3P_2 ~ 3 s via M2 transition
  - 2^3P_0 J = 0 -> 0 absolutely forbidden

- We have already measured
  - 2^3P_1 ~ 5.7 ms via E1 transition



2^3P_2 - 1^1S_0 decay rate

Hodgman et al., *Phys. Rev. A* **80**, 044501 (2009)

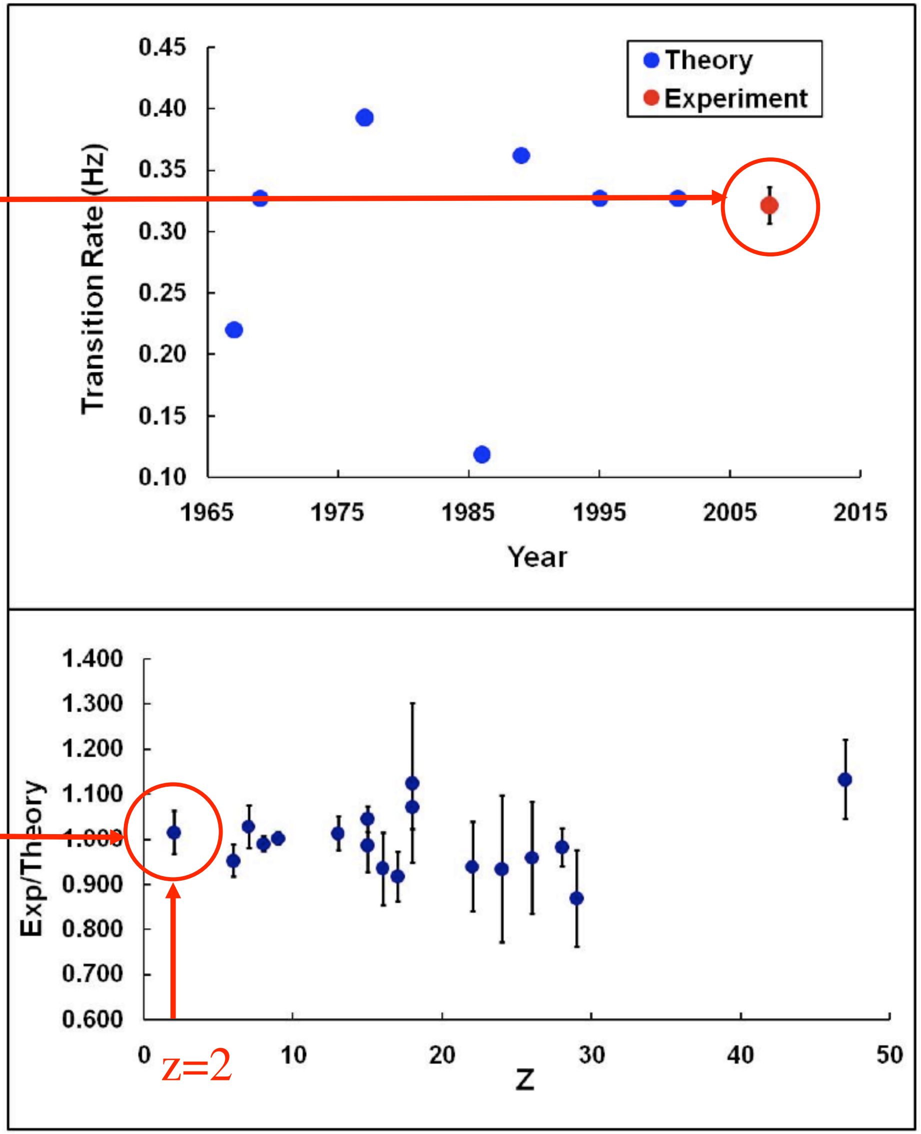
- First experimental measurement

- Consensus predicted for decay rate ~ 0.327 s^{-1}

- Our measurement for decay rate ~ 0.324(16) s^{-1}

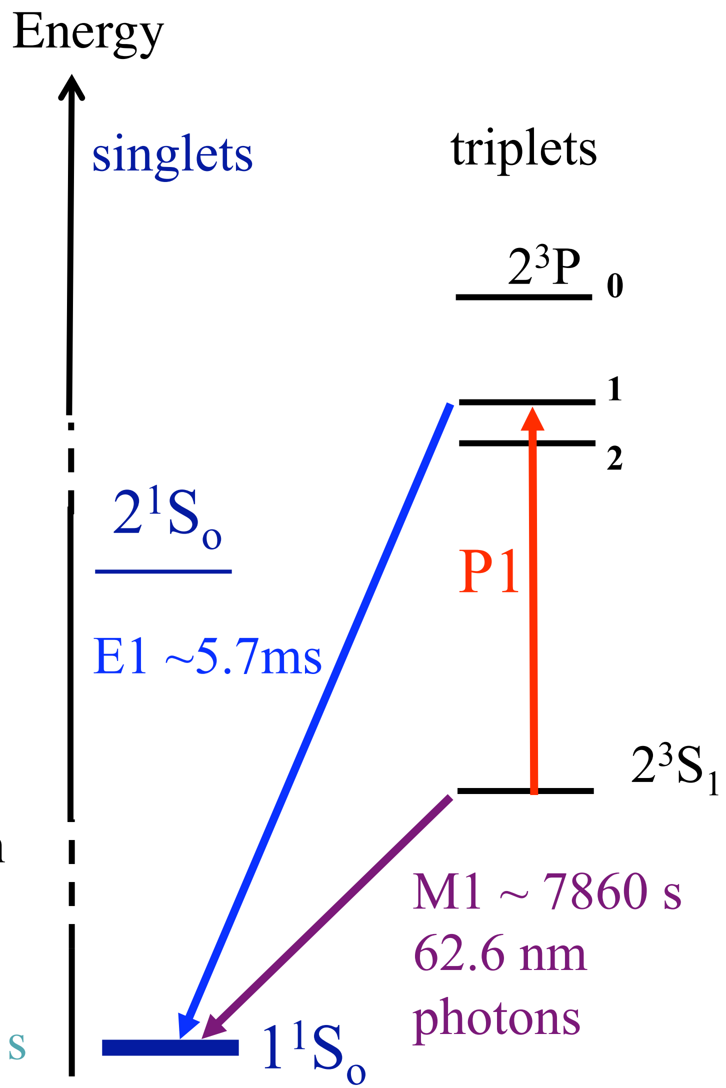
- Anchoring the iso-electronic sequence

- Upper limit on 2^3P_0 decay rate < 0.01 Hz



Metastable He: 2^3S_1 lifetime

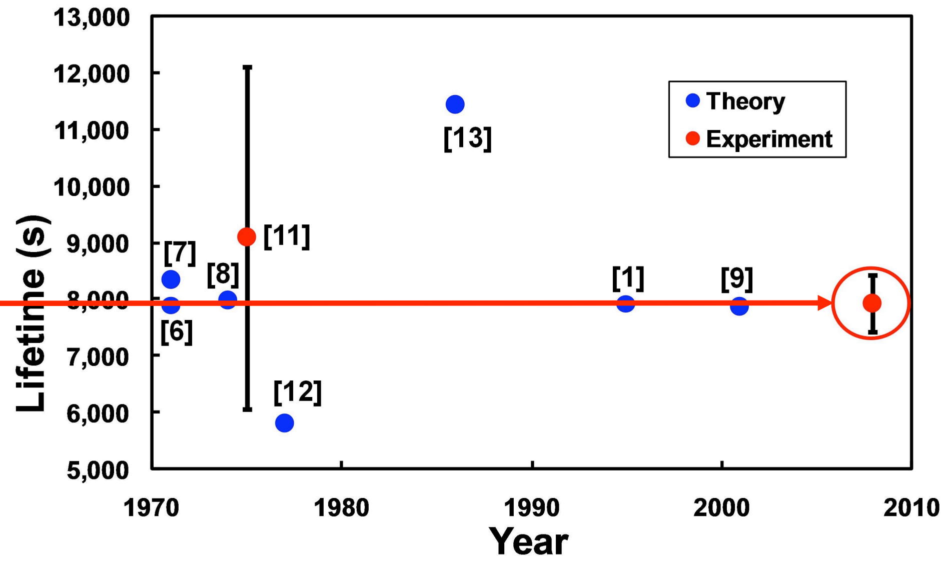
- Theory predicts a 2^3S_1 lifetime of:
  - ~ 7860s via M1 transition
- Decay via XUV radiation at ~ 62.6 nm (~ 20eV)
- Measure the XUV emission from ~ 10^8 ultracold He* atoms in *magnetic trap*
- Need only to measure the ratio of 2^3S_1 intensity to 2^3P_1 XUV emission flux, and use the 2^3P_1 decay rate measured in our first experiment as a calibration
- Correct for detector response at both λ' s



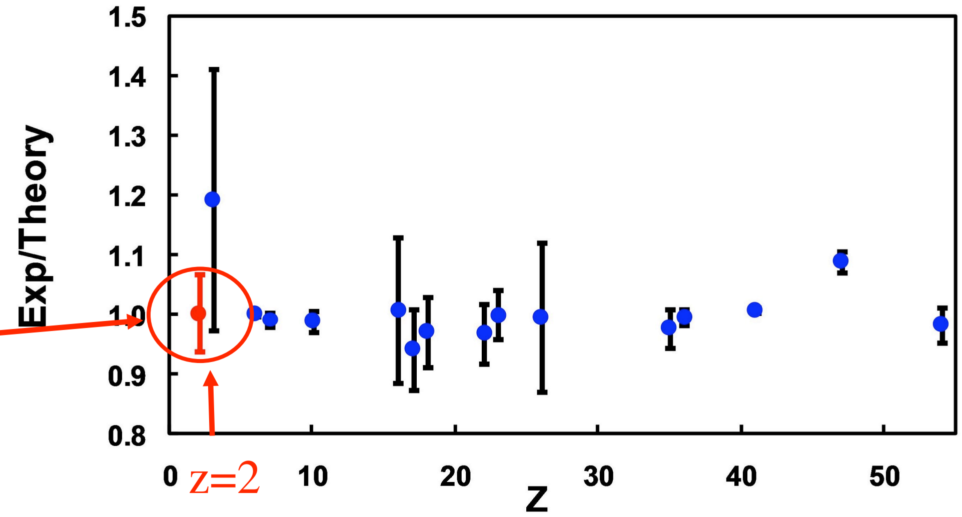
2^3S_1 lifetime

Hodgman et al., *Phys. Rev. Lett.* **103**, 053002 (2009)

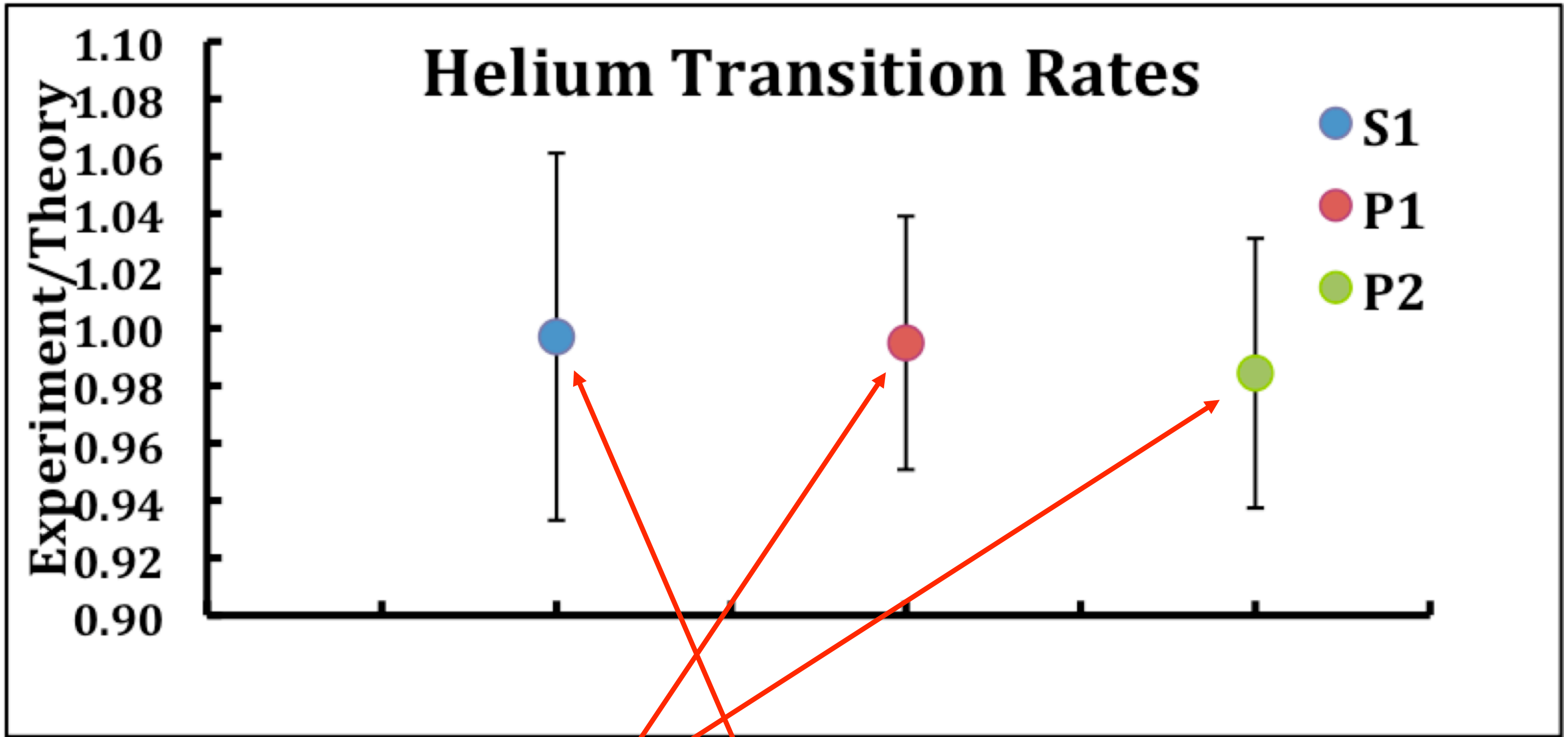
- Ours is the second measurement



- Predicted lifetime ~ 7860 s
- Our measurement ~ 7920 (510) s
- Anchoring the iso-electronic sequence



Summary



- First measurement of 2^3P manifold decay to the ground state
- Second measurement of the He* lifetime – 7920 (510) s
- All measurements are in excellent agreement with QED

Take Home Messages

LECTURE 1:

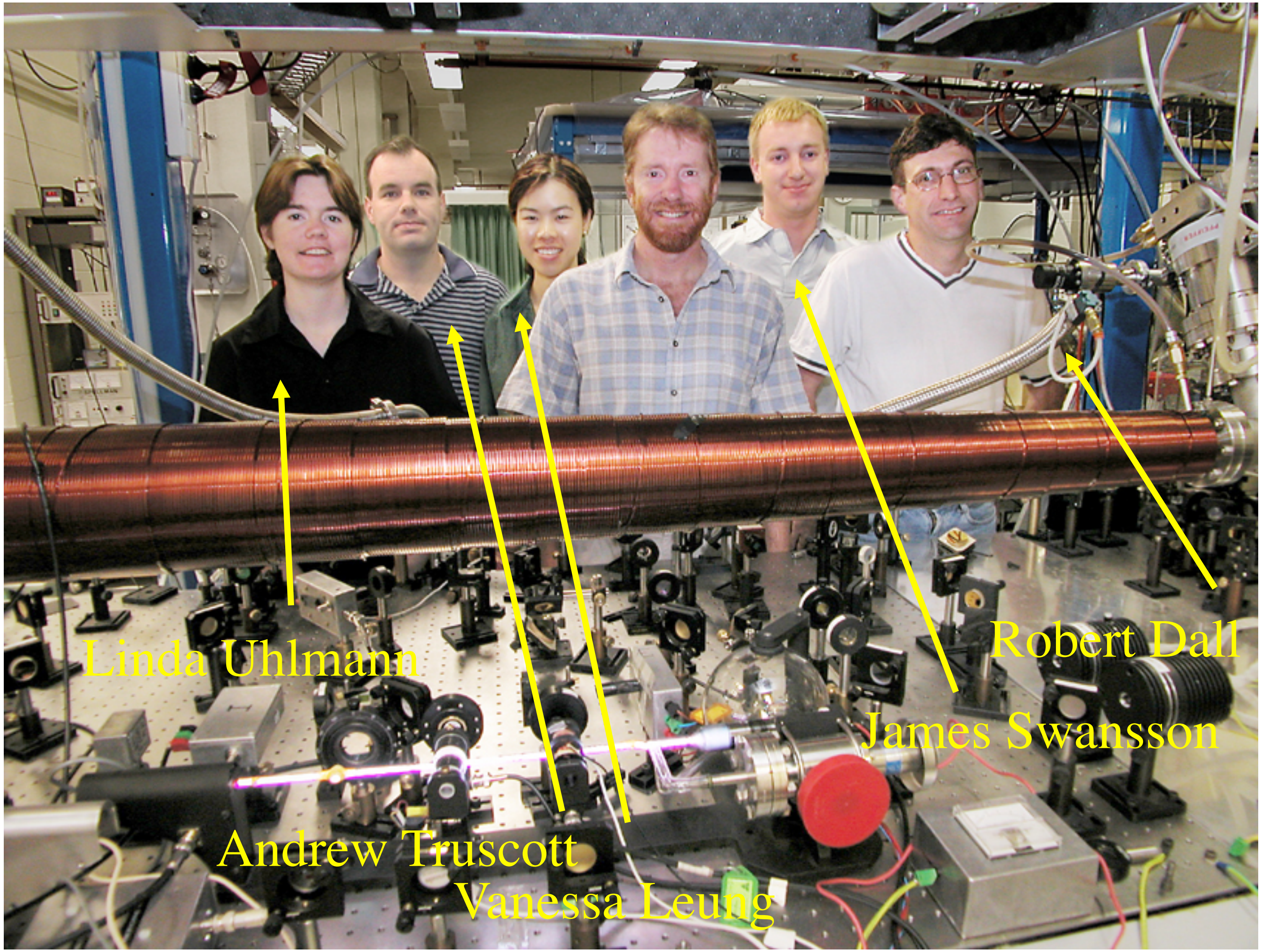
- He* 2^3S_1 has a long lifetime (~8000s) and a large stored energy (~20eV)
    - acts as a ground state for atom optics expts. at 1083nm / 389nm
    - allows single atom detection with low background

- He* hard to make - need a "bright beam line" to provide a useful source
    - 3×10^{10} He*/s/steradian in $2mm^2$ area
    - 10 - 100 m/s with 10mrad divergence

- Applications to atom optics that exploit the properties of He*
    - Atom lithography - He* stored energy damages photoresist
    - Guiding in hollow optical fibres - low counts, zero background

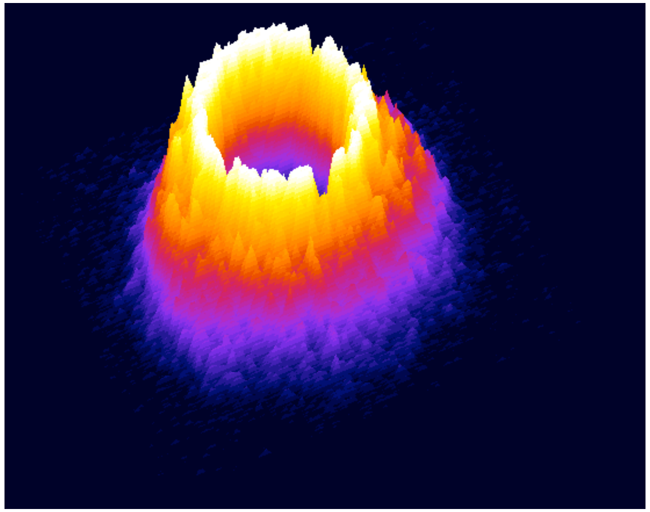
- Applications to atomic physics
    - Measure He*-e^- collisions in a controlled MOT environment
    - Measure He* state lifetimes with unprecedented sensitivity

Bright Atom Workers

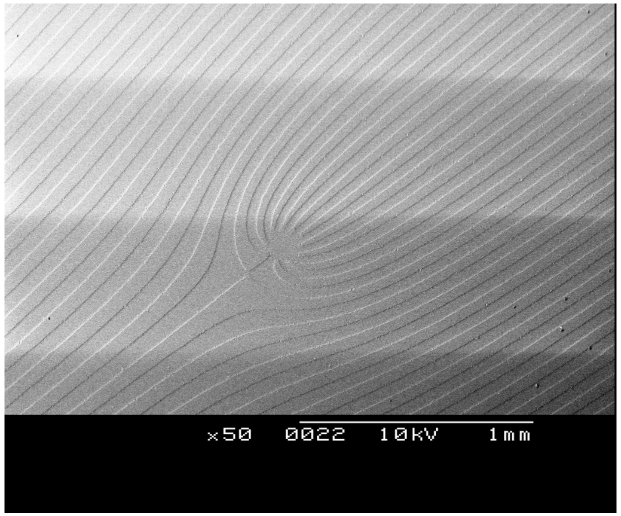


Blue Lake, Snowy Mountains,
Australia, 2004

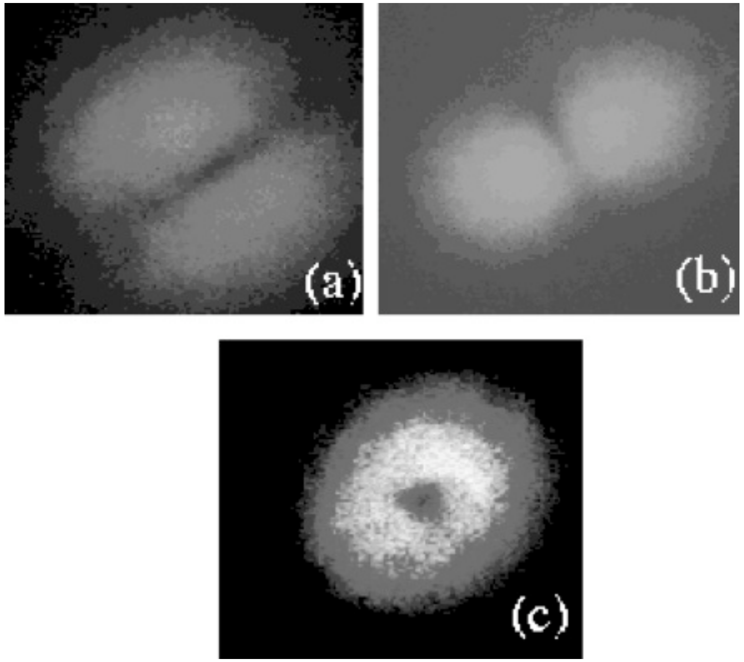
Hollow light beam generation



Light transmitted through fibre:
(a) and (b) orthogonal polarisation modes
(c) sum of two modes creating hollow
beam with zero field at centre

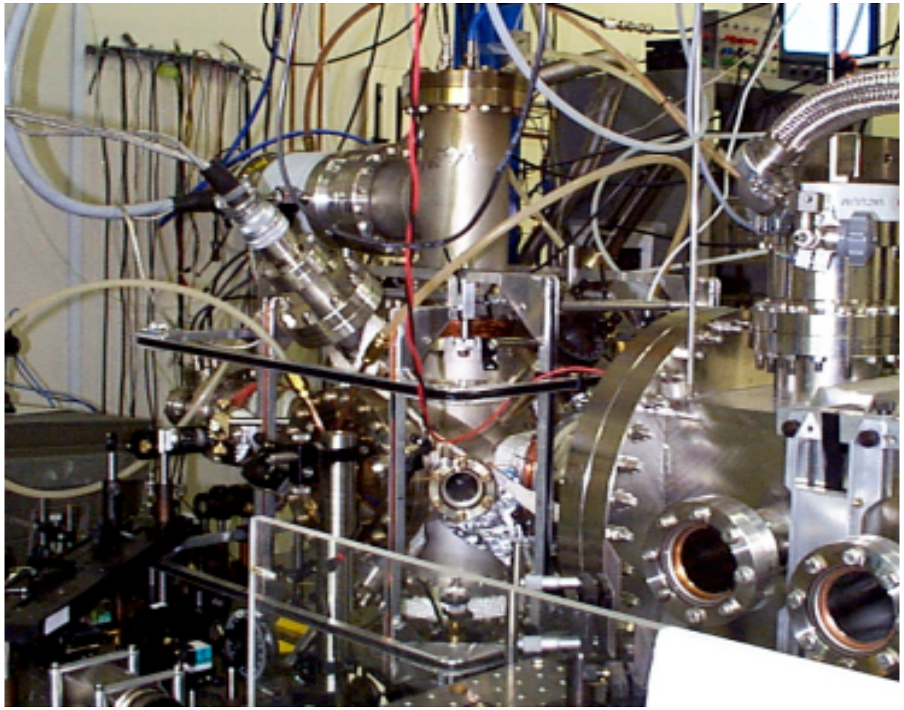


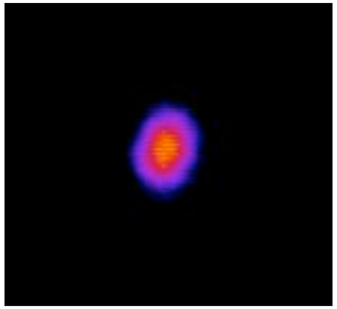
Hollow light beam made by phase mask



He* Magneto Optic Trap

- Base pressure ~ 10^{-10} Torr
- B field gradient up to 30 G/cm *plus* large detunings ~ 20 - 30 Γ
  - large capture velocities ~ 70m/s
- PI limited density ~ 5 x 10^{9} cm^{-3}
- Large trap beam diameters ~ 35 mm
  - to yield large atom numbers
- Need large laser powers ~ 200 mW
- No. of trapped atoms ~ 2 x 10^{9}
- Trap diameter ~ 8 mm
- MOT Temperature ~ 1mK
  molasses => 300 μK
  v ~ 1 m/s

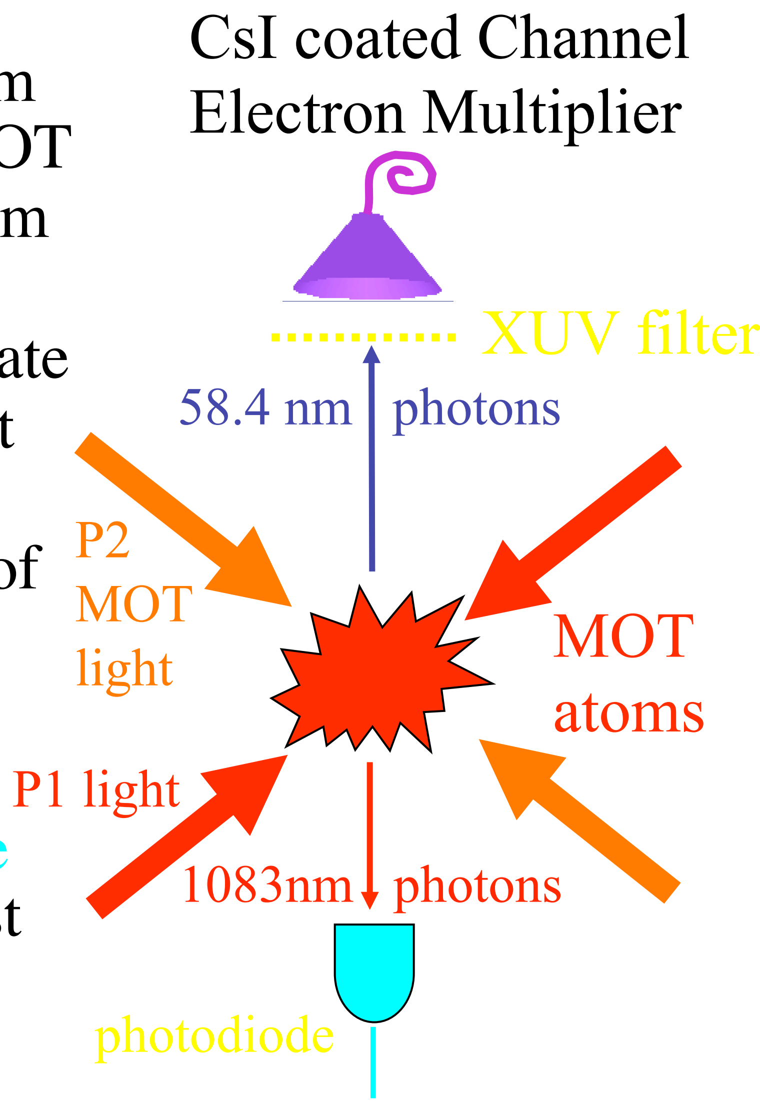




Trapped atoms fluorescing at 588nm ($2^3P \rightarrow 3^3D$ transition)

He 2^3P_2 & 2^3P_0 decay: experiment

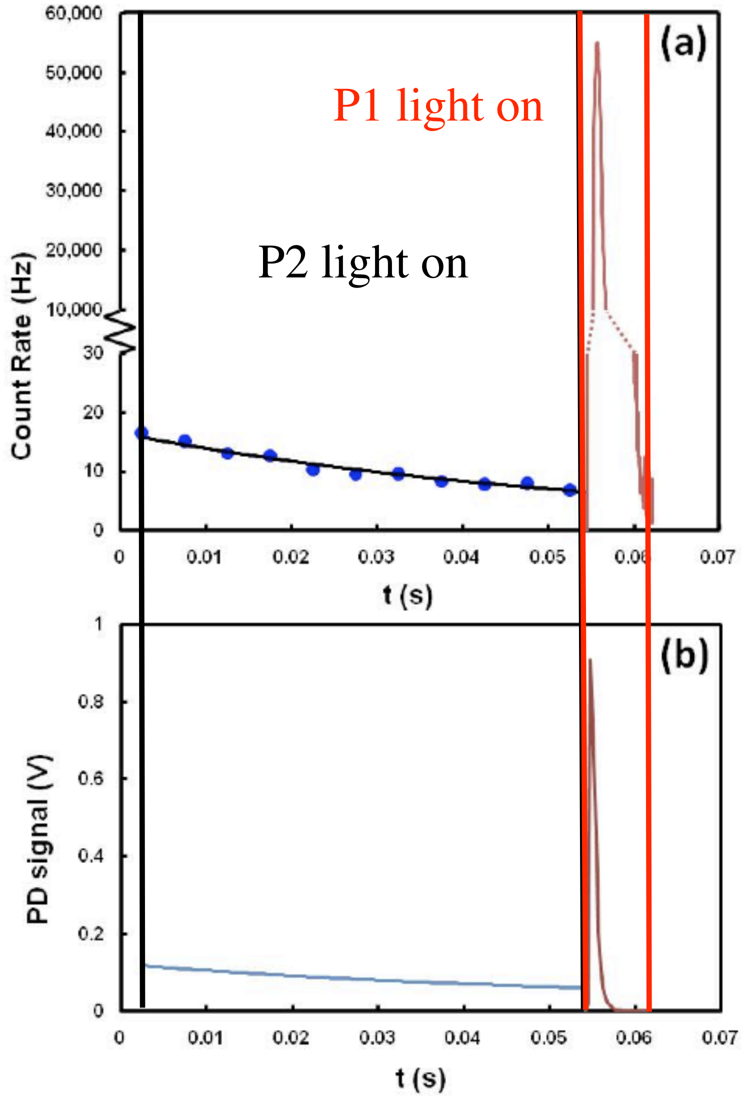
- Measure the XUV emission from $\sim 10^8$ 2^3P_2 or 2^3P_0 atoms in a MOT and filtering out radiation > 70nm
- Calibrate using the 2^3P_1 decay rate measured in our first experiment
- Need only to measure the ratio of 2^3P_2 or 2^3P_0 to 2^3P_1 count rate
- Don't need to measure the absolute number of atoms or the detector quantum efficiency, just the relative populations



$2^3P_2 - 1^1S_0$ decay rate

- 58.4 nm XUV photon channeltron count

- 1083 nm photodiode signal



Experimental analysis

- e^--He 2^3S_1 collisions cause 100% efficient trap loss due to ionisation, momentum transfer, super elastic scattering
- When the electron beam is on, atoms are ejected from the trap at a (total) rate given by

$$\Gamma_e = \sigma J/e$$

σ - total scattering x-section; J - current density

- Γ_e is determined by recording the number of trapped atoms as a function of time and fitting the data assuming

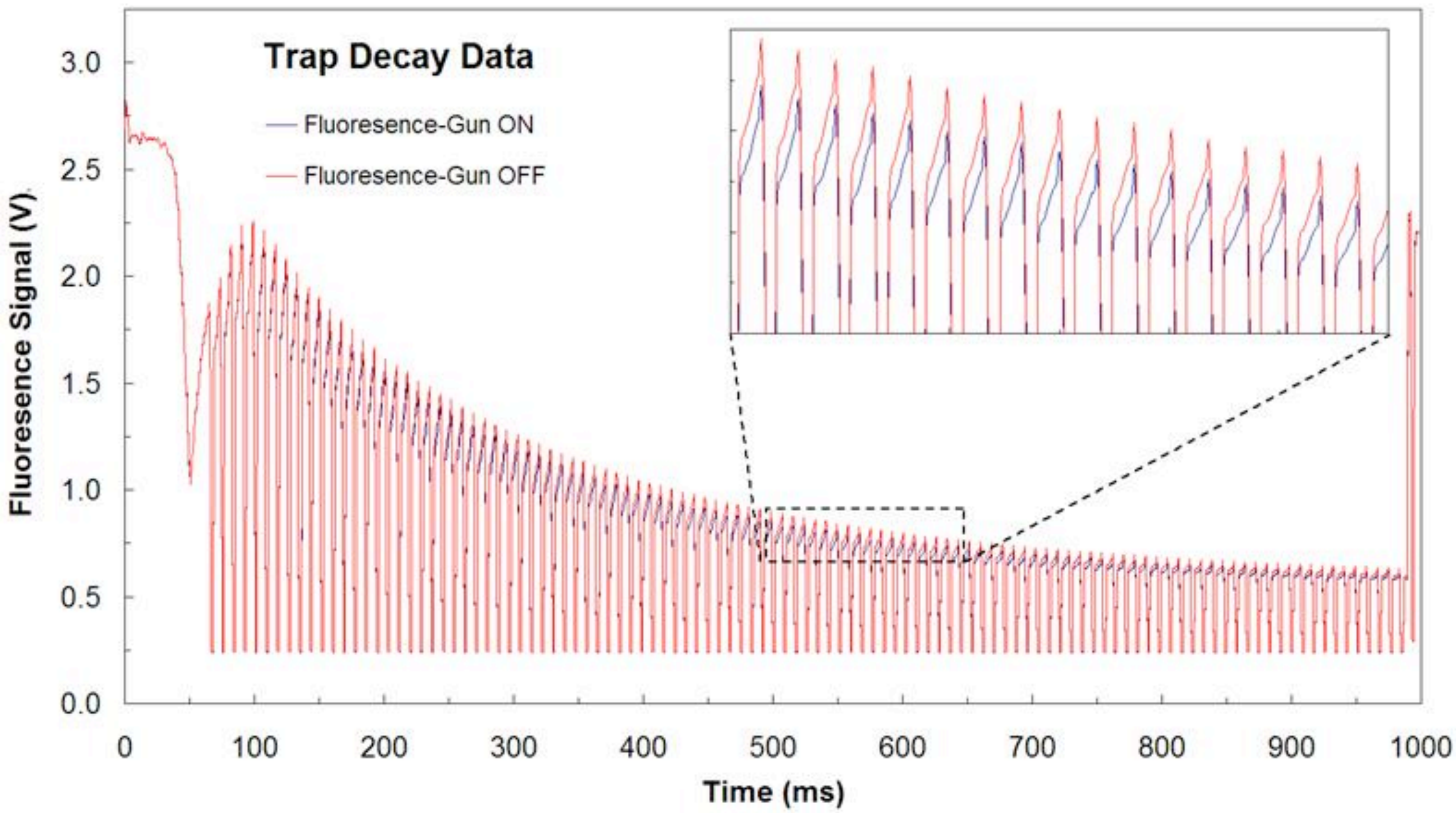
$$dN(t) \,/\, dt \;=\; L - (\Gamma_o + \Gamma_e f\,)\; N(t)\;]) - \beta[N(t)]^2/V$$

L - load rate; Γ_o - natural decay; f - e^- beam duty cycle;

β - Penning loss rate; V - trap volume

Fluorescence Trap Loss

- Relative trap atom number from 1083nm fluorescence on photodiode
- Fluorescence signal intensity compared during gun on / gun off cycles



Reference

PRL **94**, 173201 (2005) PHYSICAL REVIEW LETTERS week ending 6 MAY 2005

Electron Collisions with Laser Cooled and Trapped Metastable Helium Atoms: Total Scattering Cross Sections

L. J. Uhlmann, R. G. Dall, A. G. Truscott, M. D. Hoogerland,* K. G. H. Baldwin, and S. J. Buckman†
Atomic and Molecular Physics Laboratories, Research School of Physical Sciences and Engineering, Australian National University, Canberra, Australian Capital Territory 0200, Australia
(Received 12 January 2005; published 3 May 2005)

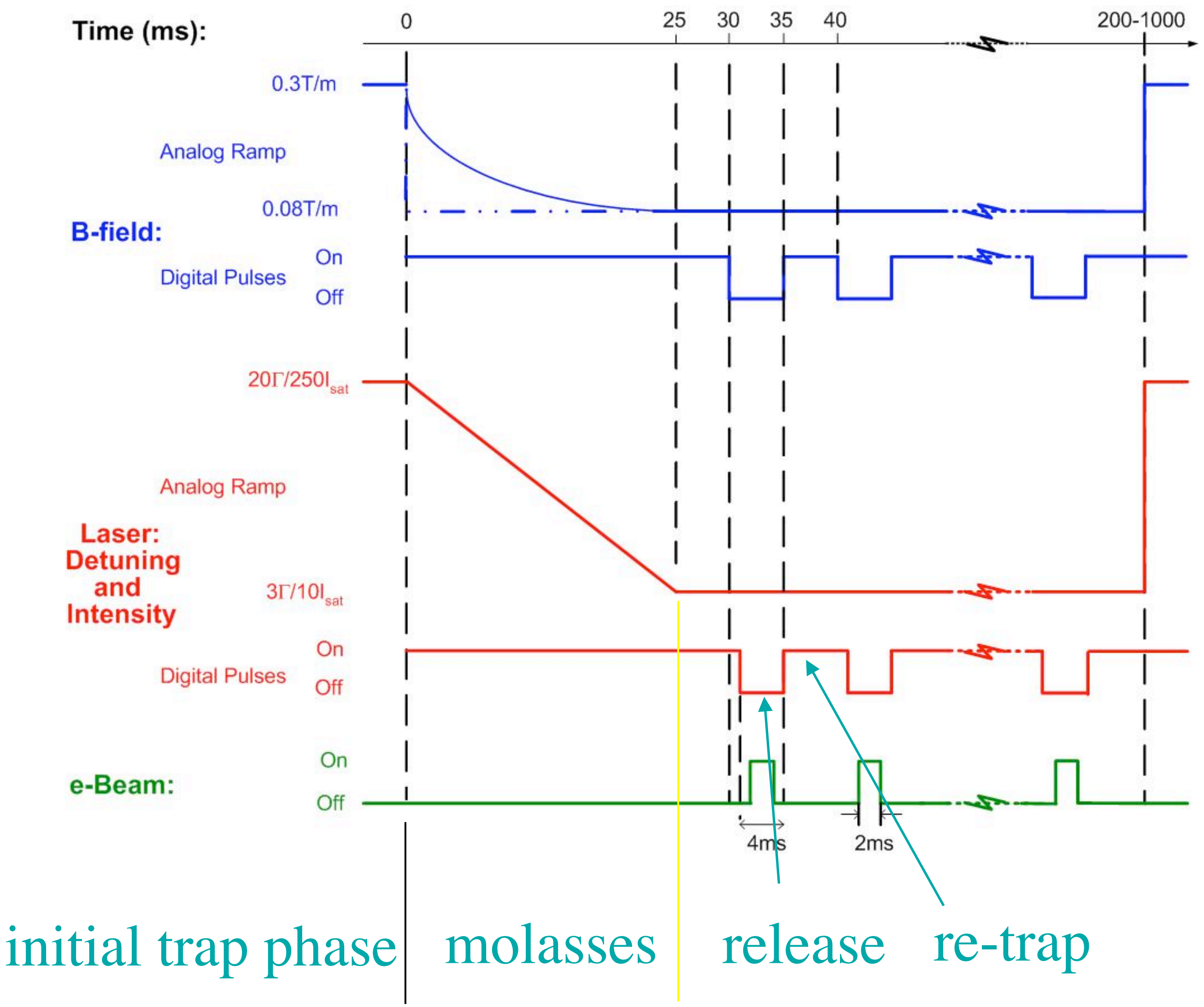
Absolute measurements of total scattering cross sections for low energy (5–70 eV) electrons by metastable helium (2^3S) atoms are presented. The measurements are performed using a magneto-optical trap which is loaded from a laser-cooled, bright beam of slow He(2^3S) atoms. The data are compared with predictions from convergent close coupling and R matrix with pseudostate calculations, and we find good agreement between experiment and theory.

DOI: 10.1103/PhysRevLett.94.173201 PACS numbers: 34.80.Dp

The measurement of absolute scattering cross sections for excited species has long been of interest to both the scattering community and to those modeling the behavior of gas discharges. Excited atoms, particularly those in metastable states, are known to have extremely large scattering cross sections. Thus, although they may be present, for example, in only a small equilibrium population in a discharge environment, the large scattering cross sections,

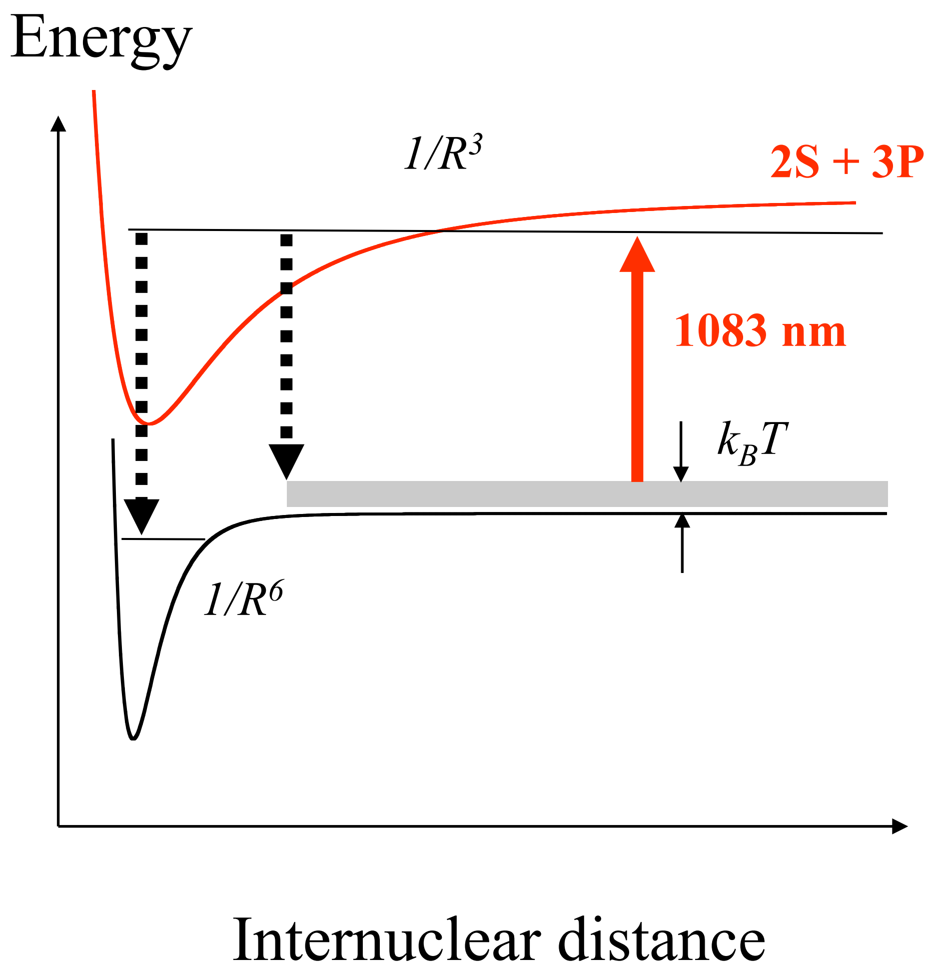
Measurements of absolute cross sections for such species are notoriously difficult, mainly as a result of the absence of reliable, high-density sources of excited atoms [8,9]. Experiments at the exit of discharge sources are most common but are typically plagued with background problems from electrons, ions, and photons. They are also contaminated by ground state species, with typically only one in 10^5 of the atoms in the excited state. Perhaps the

Trap and Release Sequence



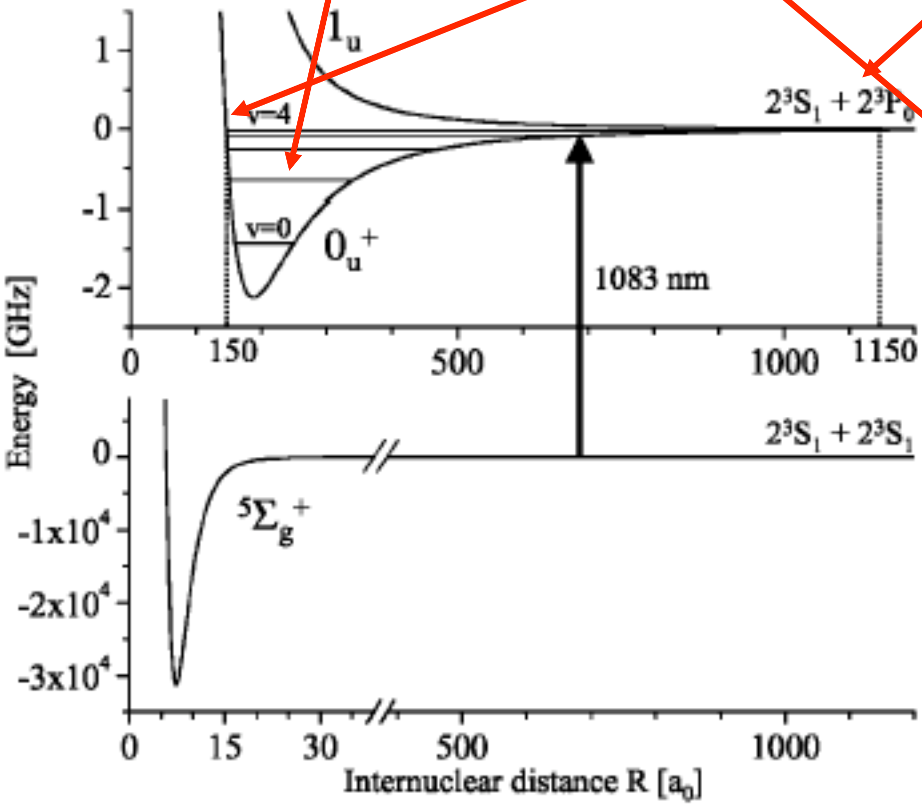
Ultracold light-assisted collisions

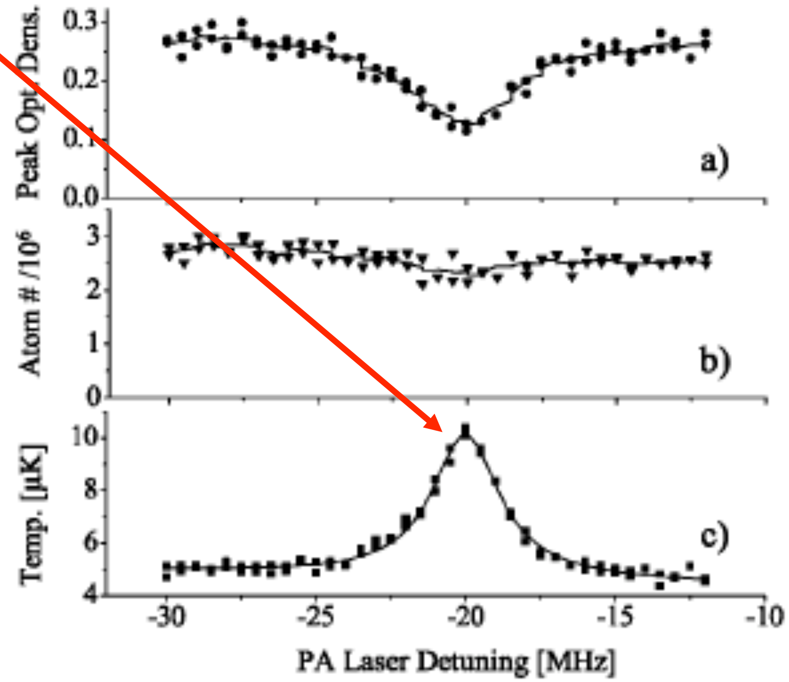
- Laser excitation of an unbound pair of atoms to a bound state in a molecular potential well
- Spontaneous and/or stimulated decay back into the bound or free S+S state
- Dissociation produces higher velocity atoms
- Measure trap temperature or trap loss to detect resonances



Giant helium dimers

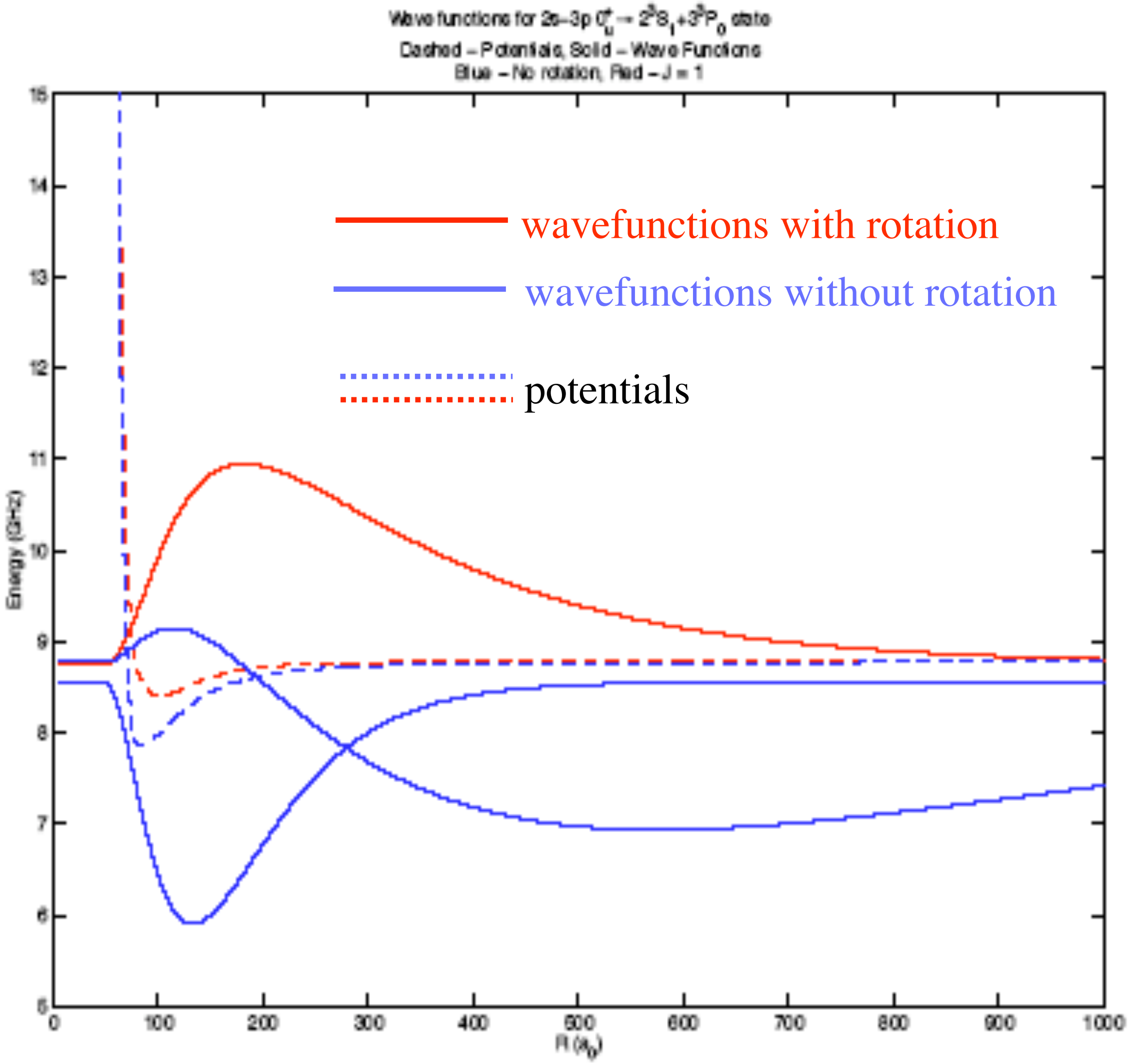
- Five bound states observed with 1083nm excitation
- All have inner turning points ~ 150 a_o, with outer turning points up to ~ 1150a_0 (> 60nm!)





J. Leonard et al., Phys. Rev. Lett. **91**, 073203 (2003)

Predicted 2S-3P Adiabatic Potentials



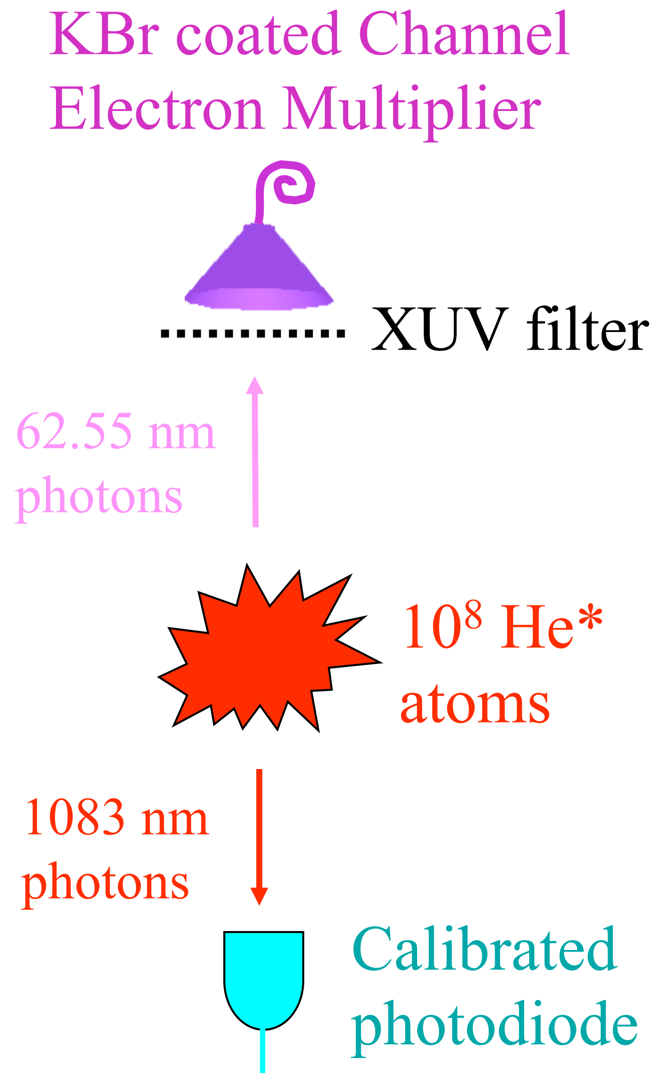
Prof. Ian Whittingham (James Cook University, Australia) predicts for 389nm excitation of the 2S - 3P levels:

- 1 long range (>50nm) state, whose position is sensitive to shape of potential
- weakly bound (25 - 40 MHz)

similar to those observed at 1083nm by ENS

Atomic physics: He 2^3S_1 lifetime

- Theory (Drake PRA **3**, 908, 1971) predicts ~ 7860 s lifetime
- Decays via magnetic dipole radiation at ~ 62.55 nm (~ 20 eV)
- Best measurement by Moos and Woodworth (PRA **12**, 2455, 1975) in a discharge source is ~ 9000s with 30% uncertainty
- METHOD 1: Aim to measure the XUV 62.55 nm emission from ~ 10^8 ultracold He* atoms released from a magnetic trap
- Need to accurately measure trap number and detection efficiency



METHOD 2

1. Measure the XUV decay rate of the 2^3P_1 (and possibly 2^3P_2) indirectly from trap decay

2. Measure the XUV radiative rate of the 2^3P_2 and 2^3P_1 level directly with MCP, allowing for the spatial distribution of the radiation.

3. Calibrate MCP detector in 2 using decay rate in 1.

4. Use the calibration to yield 2^3S_1 decay rate