Cold atoms for fundamental physics

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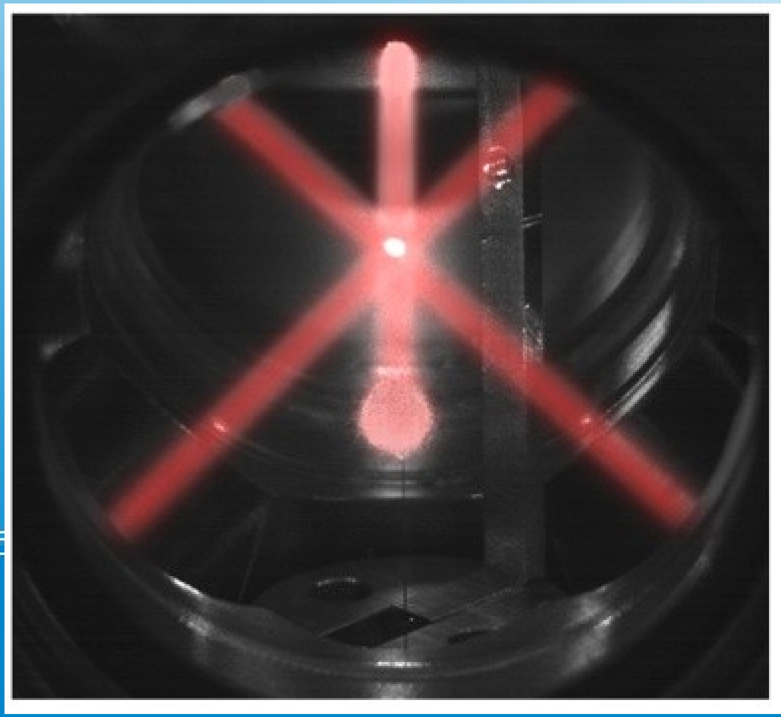
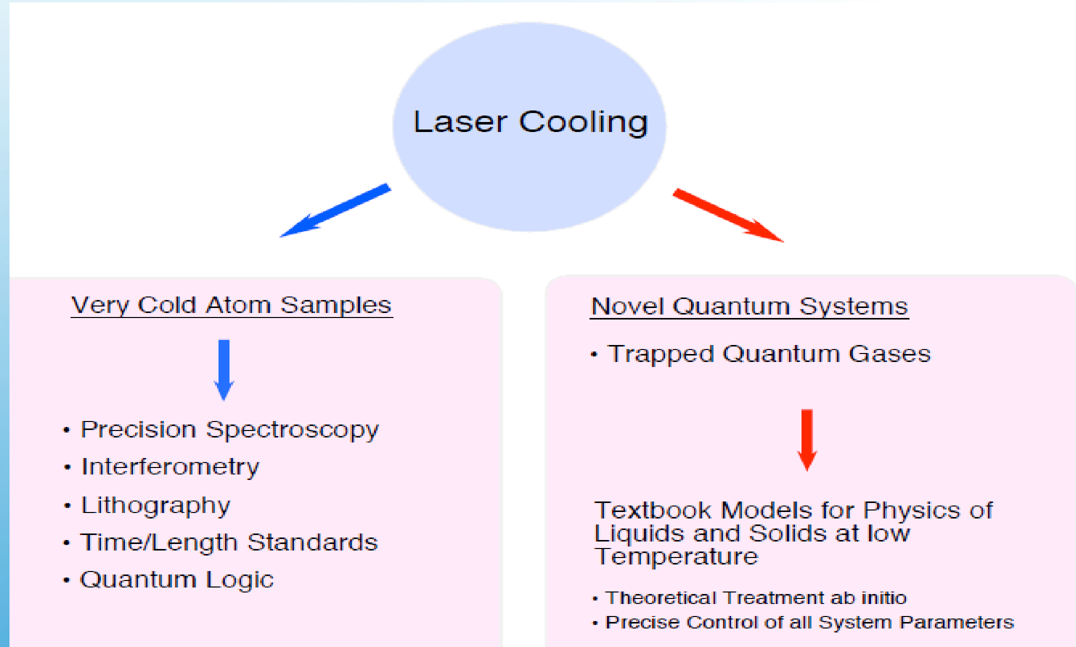
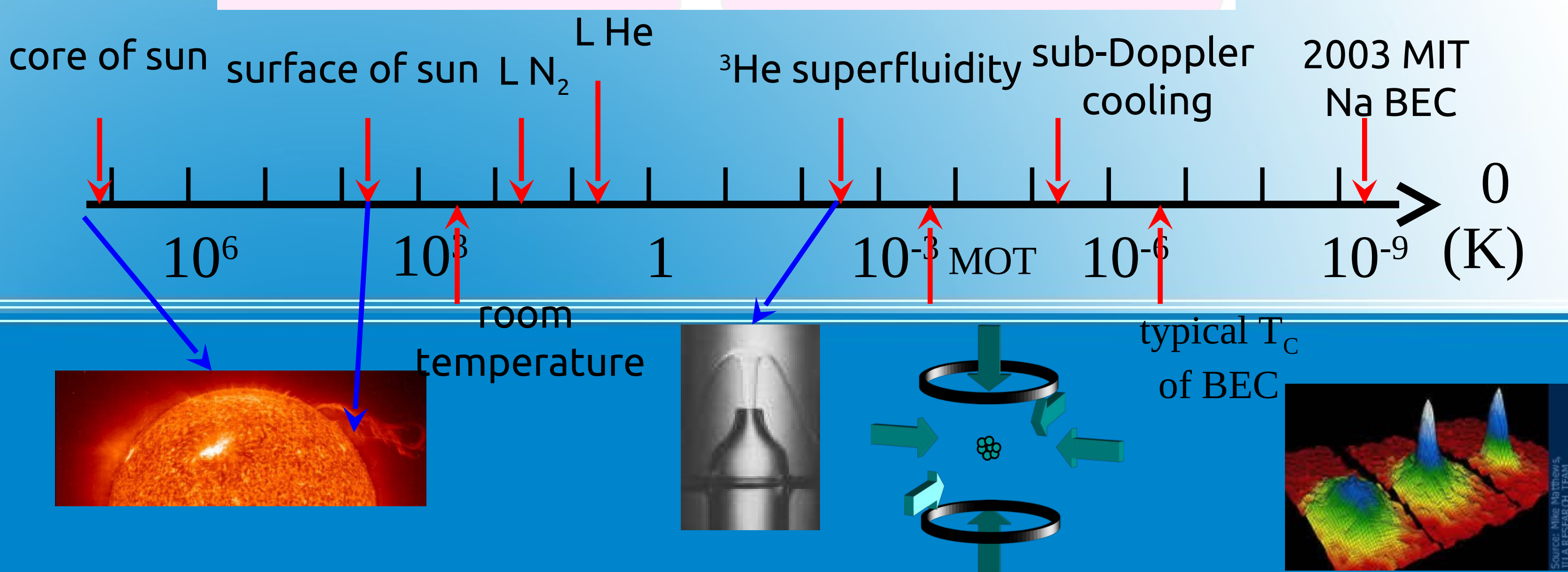
Siena, 1 aprile 2025

INTRODUCTION TO LASER COOLING AND TRAPPING



IMPORTANCE OF LASER COOLING





IMPORTANT DATES

Albert Einstein 1917: Atomic (molecular) gases thermalize in thermal light fields

Arthur H. Compton 1923: Significance of recoil in photon electron scattering

Otto R. Frisch 1933: First deflection of atomic beam by light

These experiments were performed in Hamburg, Jungiusstr. 9a, and had to be cut off, when Frisch and Stern (because of their jewish denomination) were expelled from the university.

Theodore Maiman 1960: First laser

1975	Proposals of laser cooling: T. Hänsch, A. Schalow, D. Wineland, H. Dehmelt
1980-1990	Experimental realization
1997	Nobelprize laser cooling: S. Chu, C. Cohen-Tannoudji, W. Phillips
1995	First Bose-Einstein Condensates: E. Cornell, C. Wieman, R. Hulet, W. Ketterle
2001	Nobelprize Bose-Einstein-Condensation: E. Cornell, W. Ketterle, C. Wieman

IMPORTANT DATES

The Nobel Prize in Physics 2005

John L. Hall and Theodor W. Hänsch

"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"

The Nobel Prize in Physics 2012

Serge Haroche and David J. Wineland

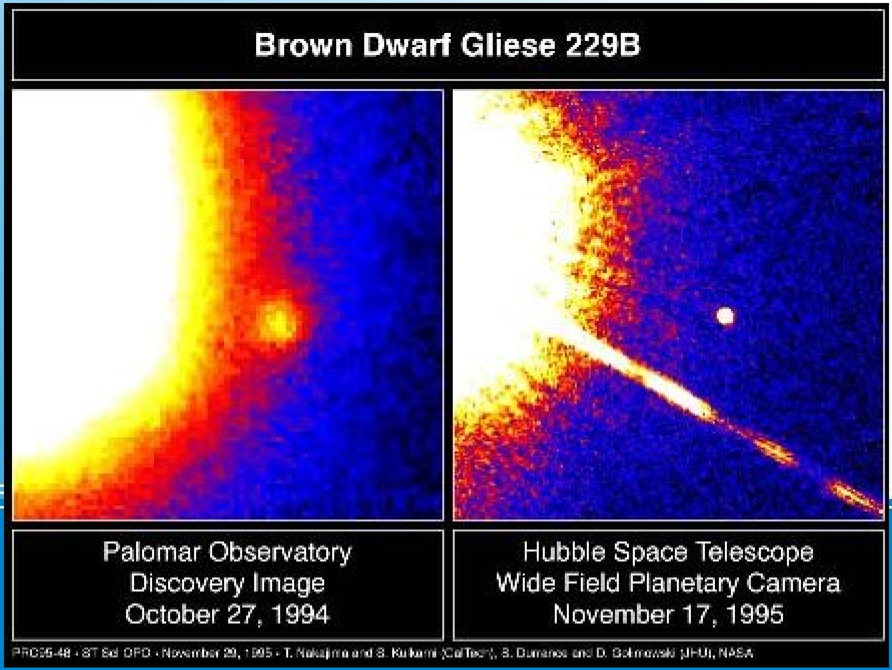
"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

RADIATION PRESSURE (CLASSICAL E.M.)

Radiation pressure bends a comet's tail.

$$P_{rad} = \frac{I}{c}$$

$$F_{rad} = \frac{\sigma_{abs} \times I}{c}$$



RADIATION PRESSURE (CLASSICAL E.M.)
NICHOLS & HULL EXPERIMENT

$$F_{rad} = \frac{\sigma_{abs} \times I}{c}$$

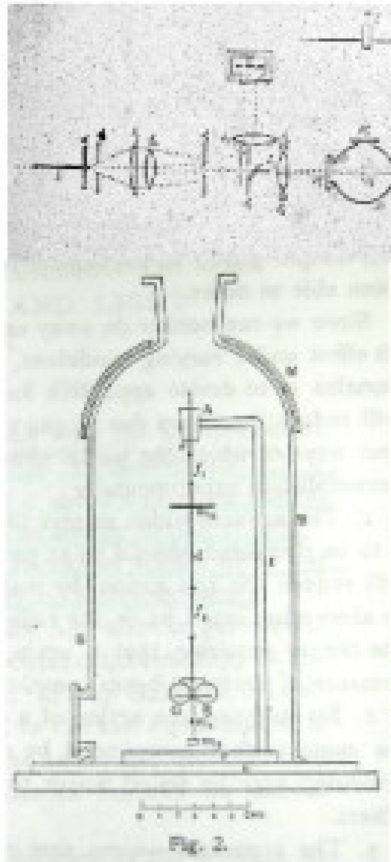


Figure 1 (Top), showing the apparatus used by Nichols and Hull in the light pressure experiment. Figure 2 (Left), showing the Nichols radiometer.

Image courtesy of the Rauner Special Collections Library.

$$P_{rad} = \frac{I}{c}$$

RESONANT RADIATION PRESSURE
FRISCH EXPERIMENT

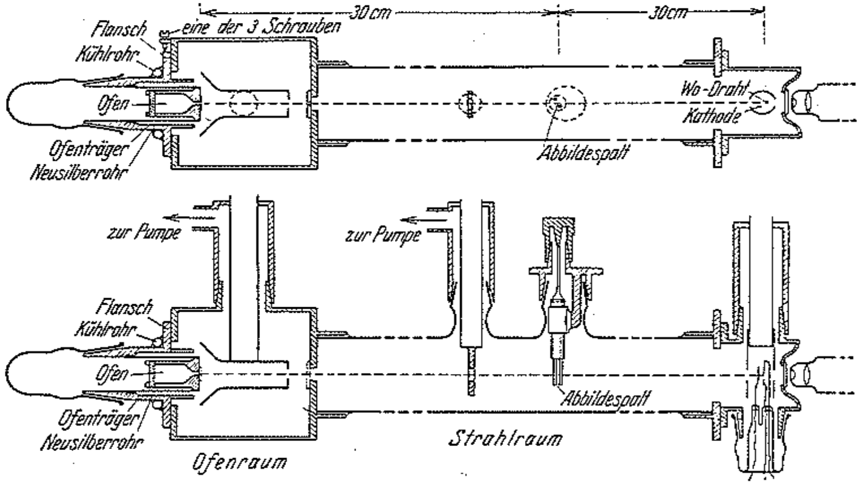


Fig. 4. Längsschnitt durch den Apparat
unten: in der Spaltebene (vertikal), oben: senkrecht zur Spaltebene (horizontal).

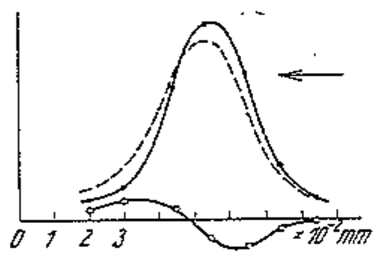


Fig. 5. Versuch mit seitlicher Beleuchtung.
Abszisse: Stellung des Auffängers.
Ordinate: Elektrometerausschlag.
—●— Intensität ohne Beleuchtung.
—○— Wirkung der Beleuchtung.
- - - - Summe dieser beiden, also Intensität mit Beleuchtung.
Der Pfeil deutet die Richtung des Lichteinfalls an.

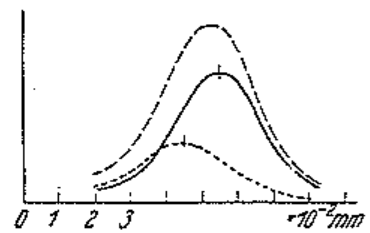
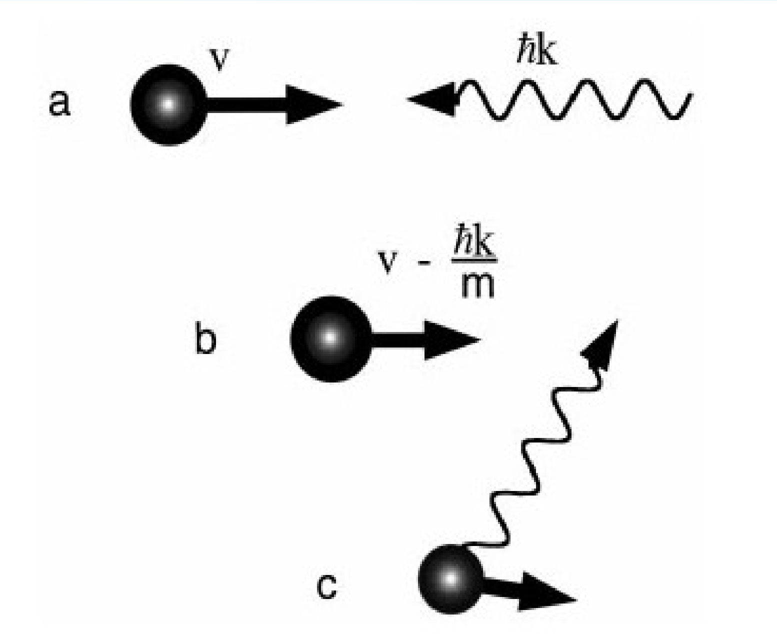
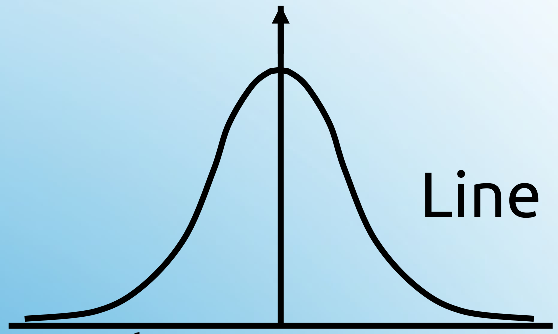


Fig. 6.
- - - - Strahl mit Beleuchtung.
——— $^2/_3$ vom Strahl ohne Beleuchtung.
· · · · · · Differenz dieser beiden, also Verteilung der abgelenkten Atome.

THE COOLING MECHANISM



$$\vec{F} = \hbar \vec{k} \Gamma$$



Line width

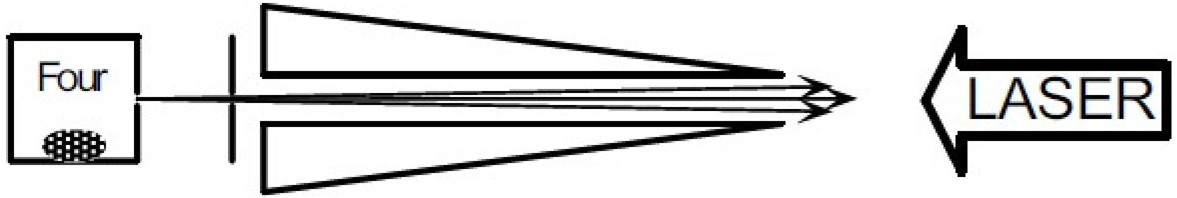
acceleration:

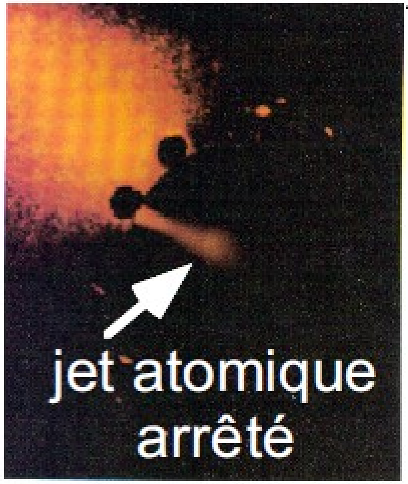
$$\Gamma(\omega) = \frac{\gamma}{2} \frac{s_0}{1 + s_0 + [2(\omega - \omega_0)/\gamma]^2}$$

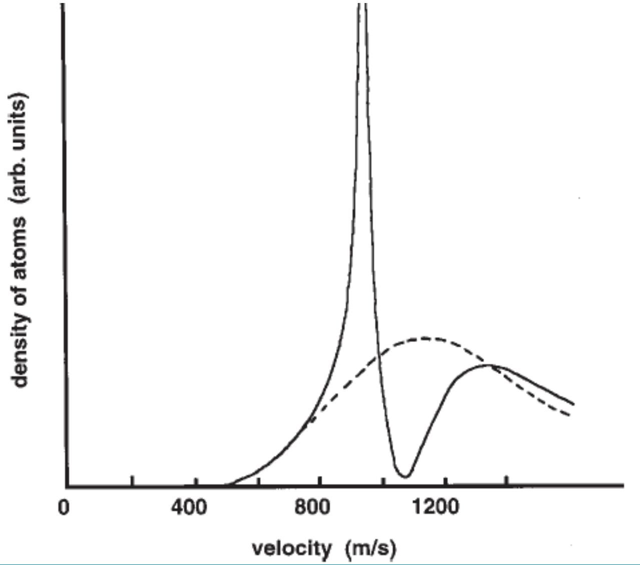
Lithium:

$$F \approx \frac{6.63x10^{-34}\,\mathrm{Js}}{671x10^{-9}\,\mathrm{m}} 6\mathrm{MHz} \approx 10^{-19}\,\mathrm{N} \qquad a = F/m = \frac{6x10^{-17}\,\mathrm{N}}{10^{-26}\,\mathrm{kg}} = 6x10^{5}\,m/s^2 \approx 10^5 g$$

RESONANT RADIATION PRESSURE
LASER ON AN ATOMIC BEAM (1D)



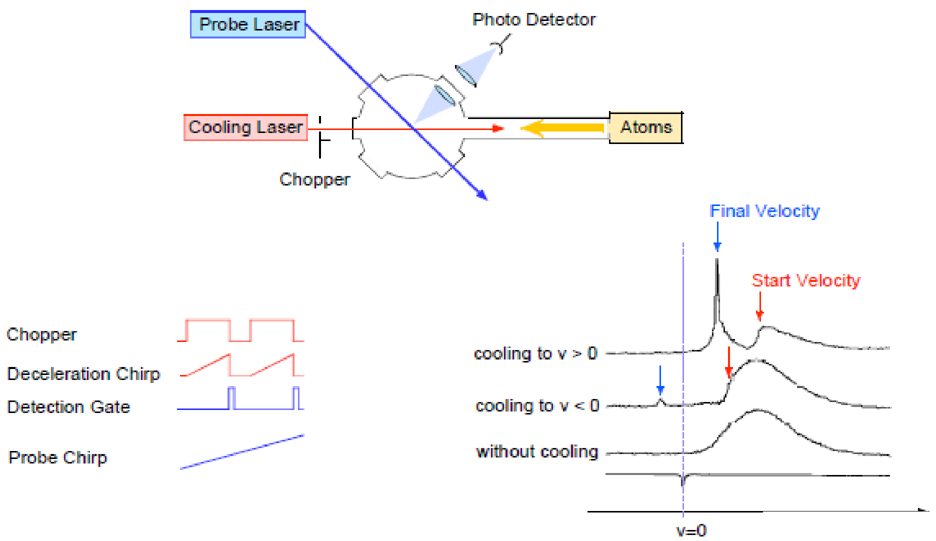




$$\vec{F}_{rad} = \hbar\vec{k}\Gamma_{scat}$$

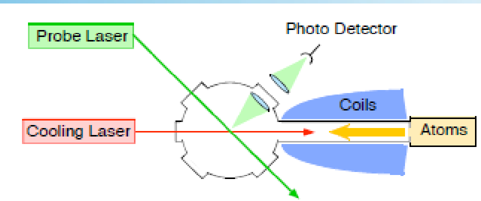
$$a_{max} = \frac{\hbar k \Gamma}{2M} = \frac{v_r}{2\tau}$$

RESONANT RADIATION PRESSURE
LASER ON AN ATOMIC BEAM (1D)



Frequency chirping

Zeeman slower

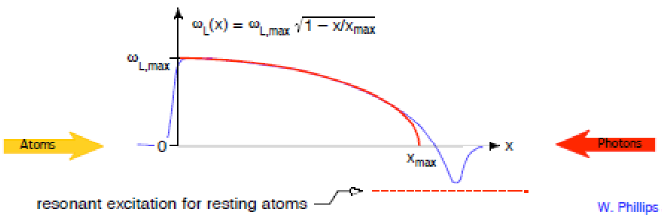


Adjusting optimal magnetic field gradient:

choose max. velocity v_{max} to be decelerated: $\Rightarrow$ stopping distance: $x_{max} = \frac{v_{max}^2}{2a}$, $a = \Pi_e \frac{\hbar k \Gamma}{m}$

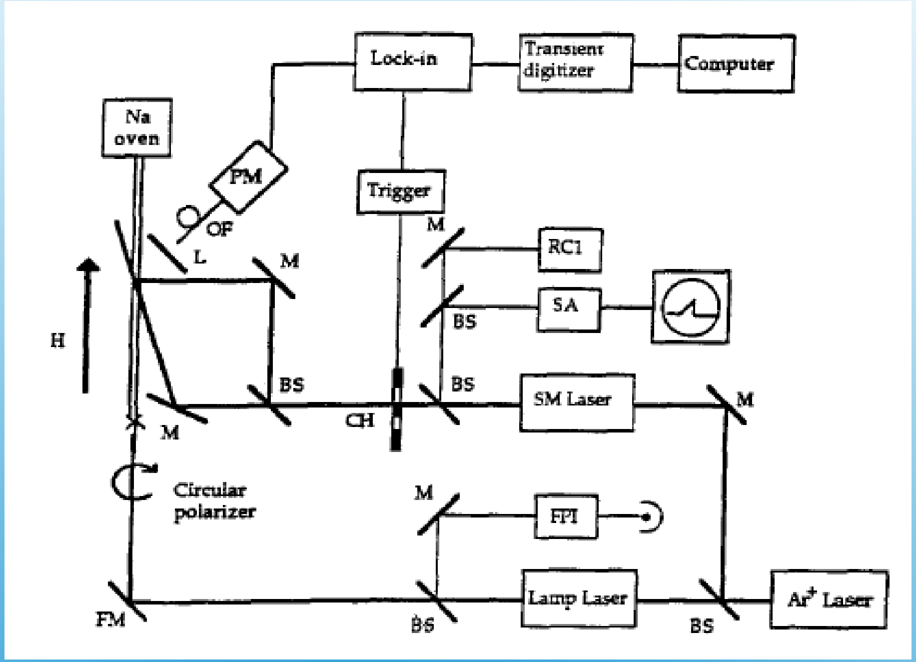
$$x(t) = v_{max}\, t - \frac{1}{2} a t^2 \quad \Rightarrow \quad v(x) = v_{max} \sqrt{1 - x/x_{max}} \quad \Rightarrow \quad \omega_L(x) = \omega_{L,max} \sqrt{1 - x/x_{max}}$$
$$v(t) = v_{max} - a t$$

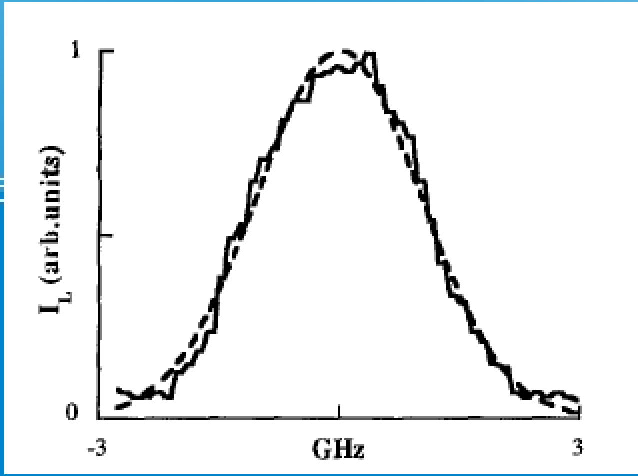
max. Lamor-frequency $\omega_{L,max} = k\, v_{max}$

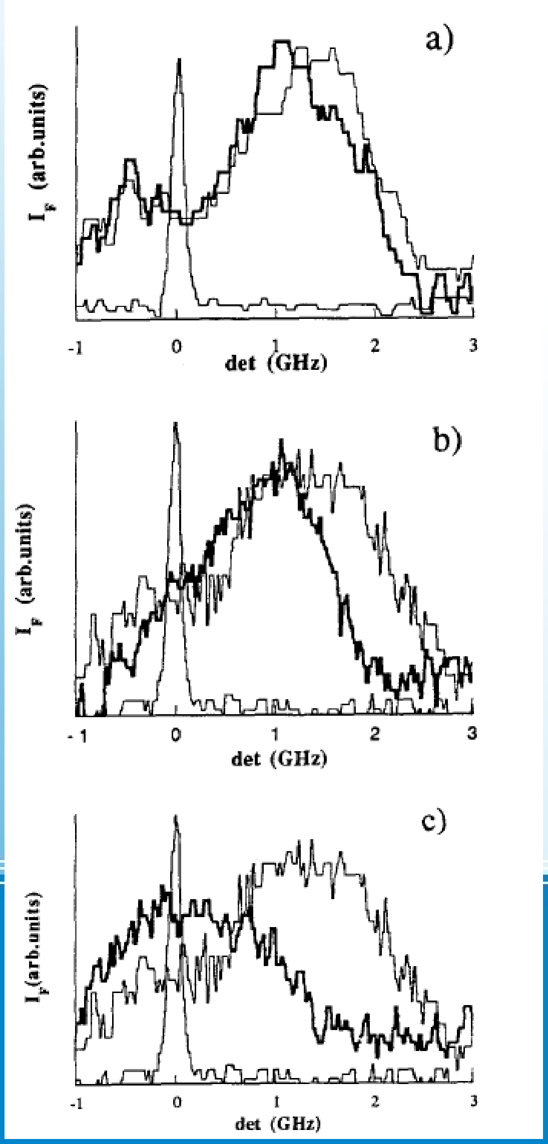


W. Phillips and H. Metcalf, Phys. Rev. Lett. 48, 596 (1982)
J. Prodan et al., Phys. Rev. Lett. 49, 1149 (1982)

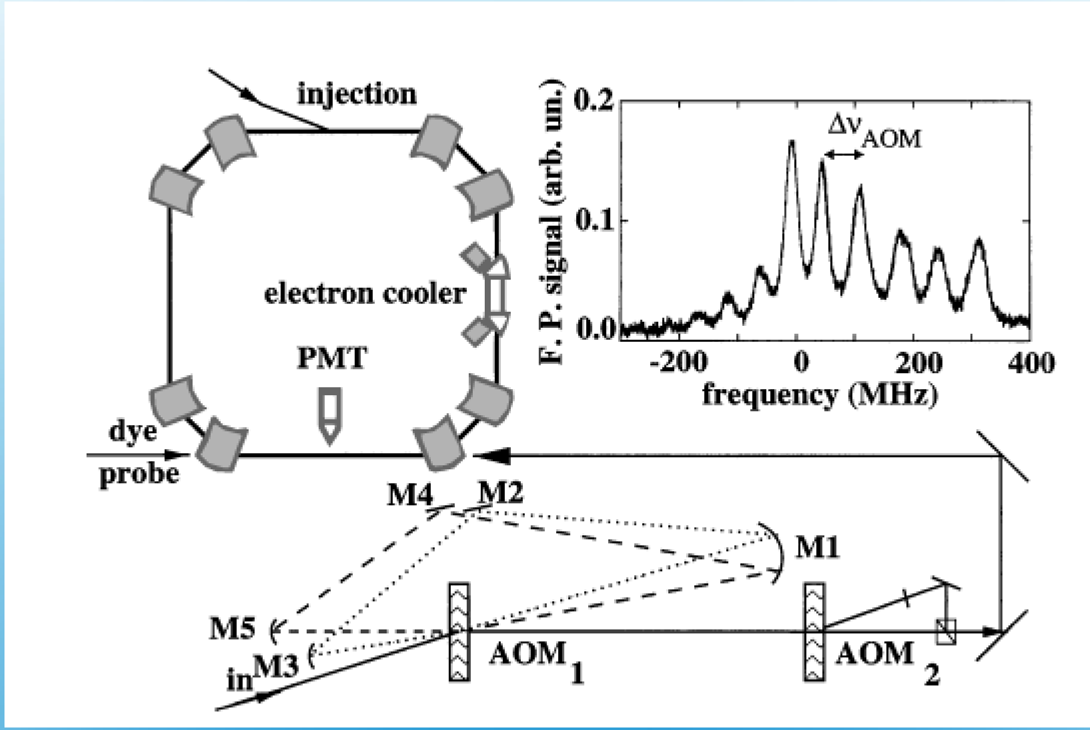
RESONANT RADIATION PRESSURE
LASER ON AN ATOMIC BEAM (1D)



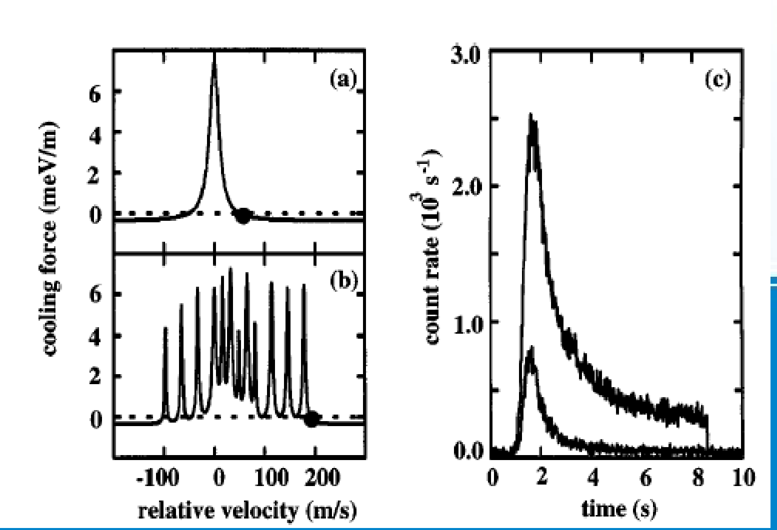




RESONANT RADIATION PRESSURE
LASER ON A IONIC BEAM (1D)

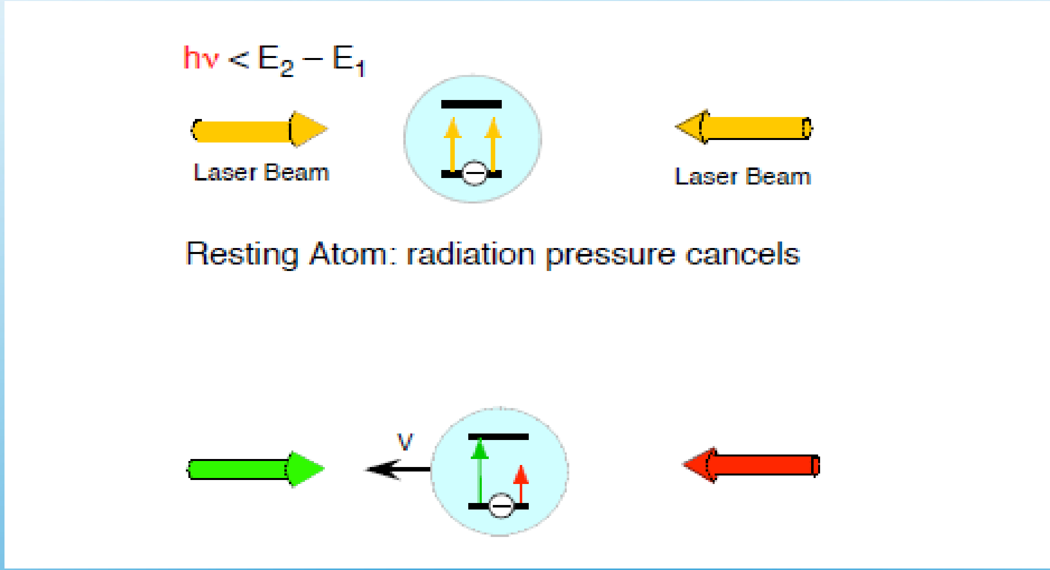


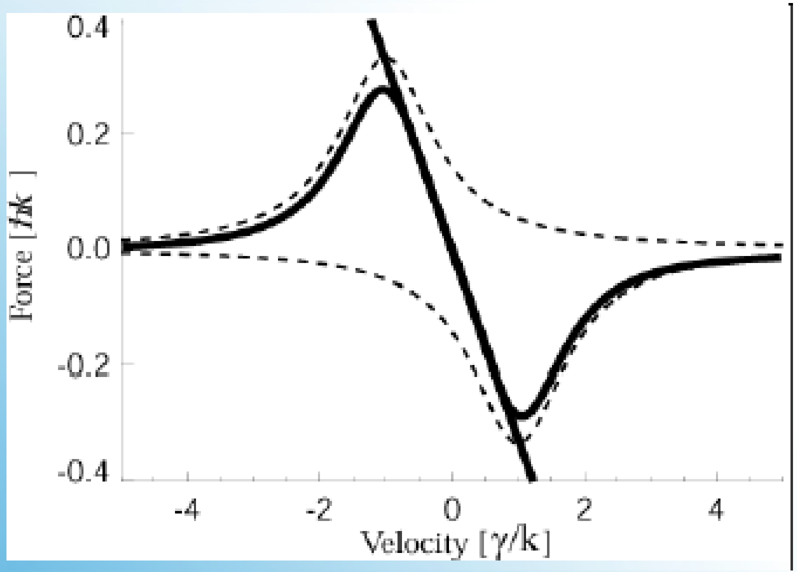
Frequency comb



Cooling = reducing the bandwidth

RESONANT RADIATION PRESSURE
LASER ON AN ATOMIC VAPOR (1D)





red detuned

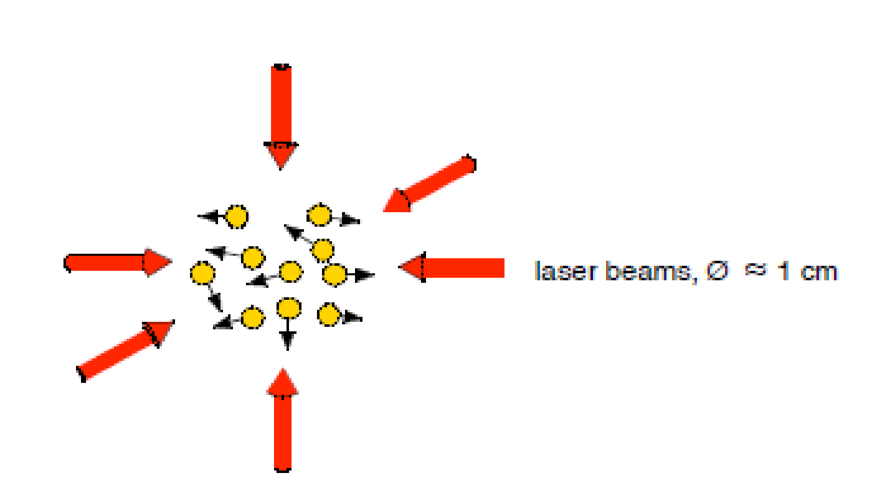
blue detuned

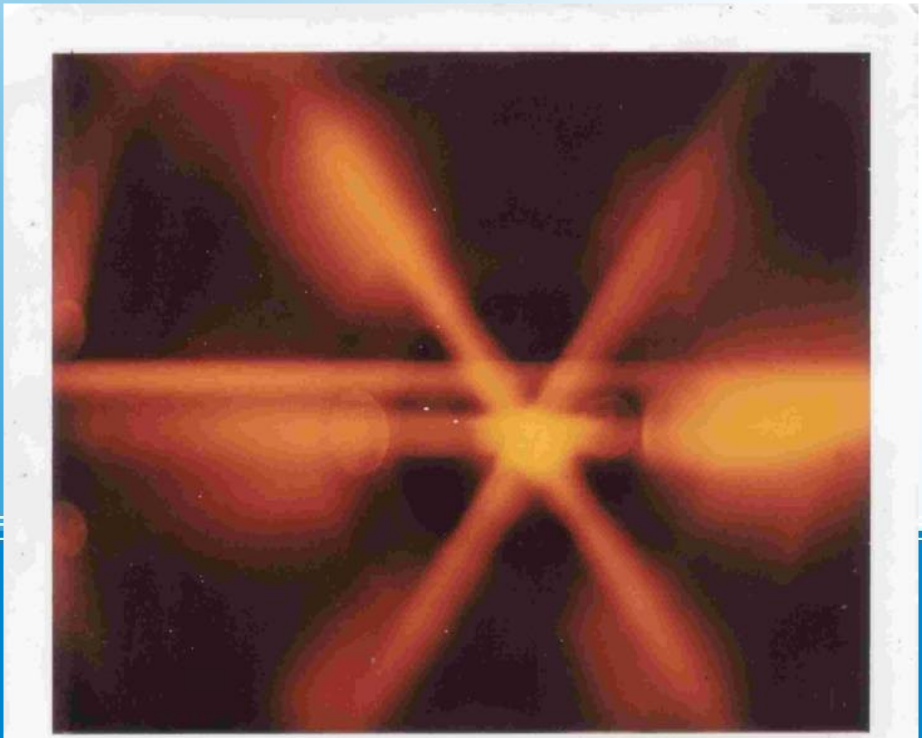
$$F_{ges} = \hbar k\left(\Gamma_1(\omega-\omega_0+kv)-\Gamma_2(\omega-\omega_0-kv)\right)$$

$$\approx \alpha v + O(v^2)$$

$$\alpha = \frac{16\,\omega_1^2\,\delta\,\Gamma}{(4\delta^2+\Gamma^2+2\omega_1^2)^2}\,\hbar k^2$$

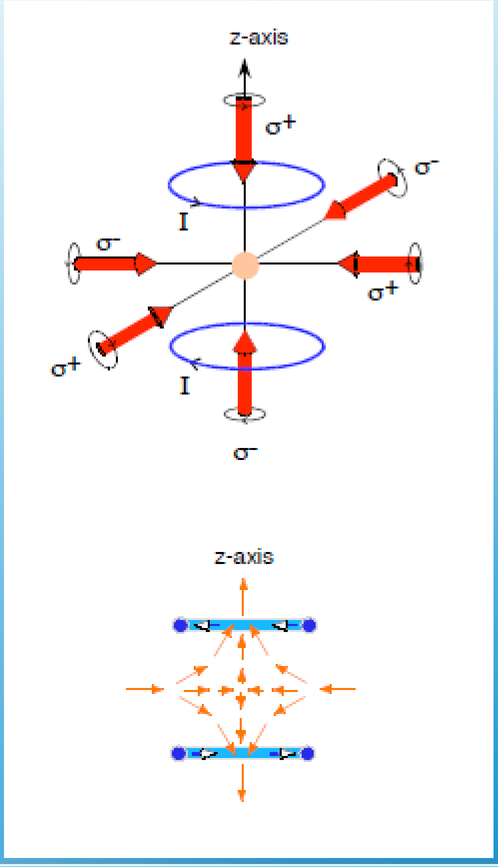
OPTICAL MOLASSES (3-D cooling)

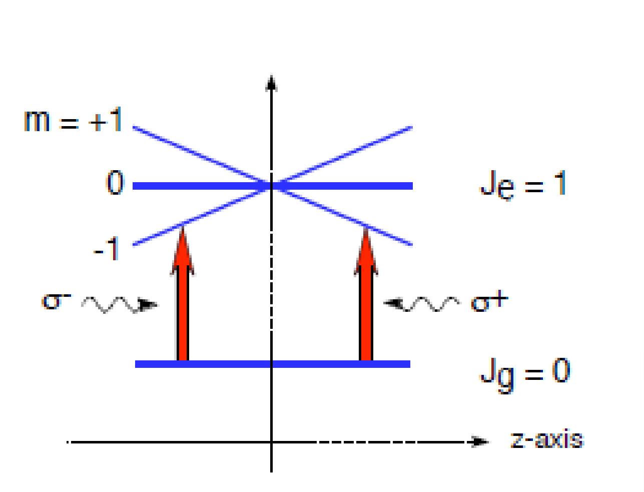




Harold Metcalf (1986)

ATOM TRAPS

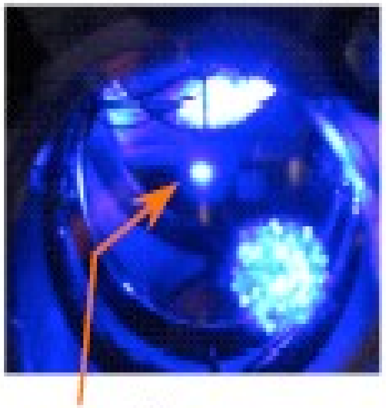




$$\frac{F}{m} = \left(\Pi_{+1}(\delta + kv + \beta z) - \Pi_{-1}(\delta - kv - \beta z)\right) \frac{\hbar k \Gamma}{m} = \gamma v + \omega_{vib}^{2} z + O(v^2, z^2)$$

ATOM TRAPS

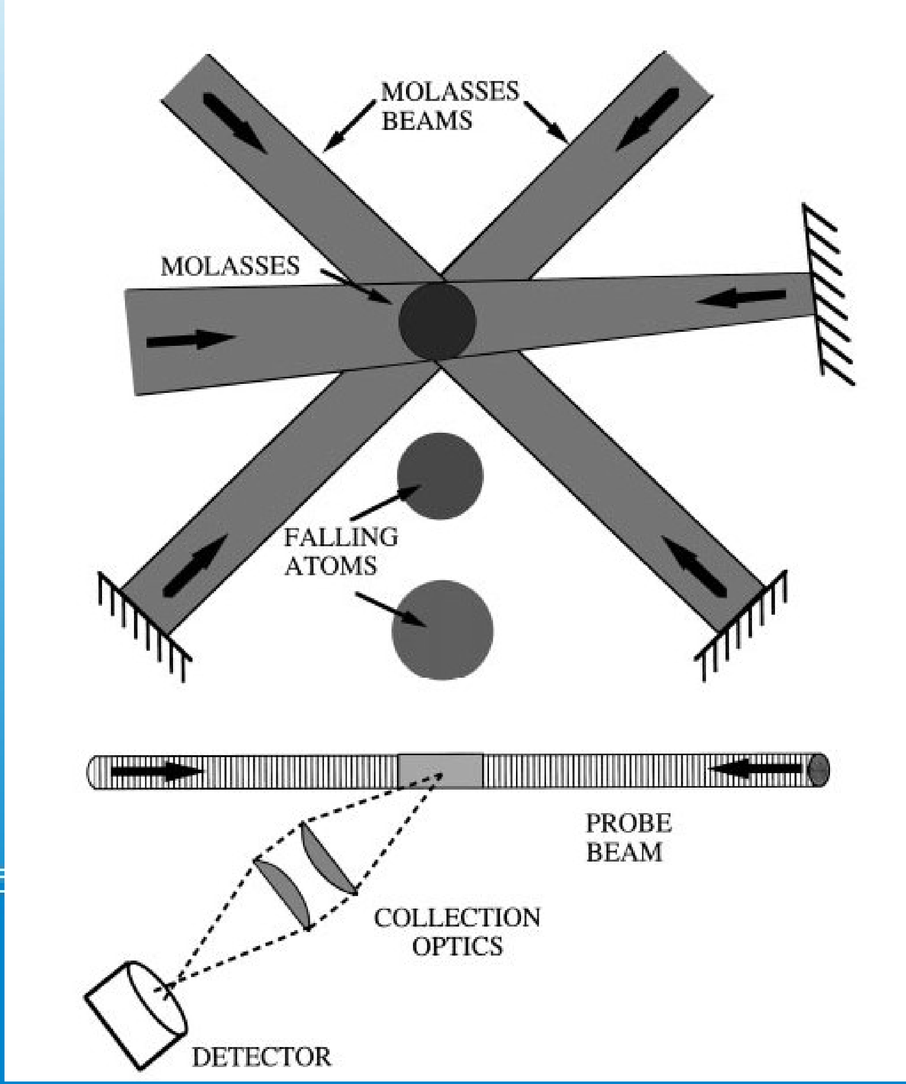
Typical MOT parameters:



trapped atoms

Diameter of Laser Beams	1 cm
Power/Laser Beam	10 mW
Detuning of Laser Frequency	1 Γ
Magnetic Field Gradient	10 Gauss/cm
Number of trapped Atoms	10^9
Peak Density of trapped Atoms (Limited by Fluorescence)	10^{11} atoms/cm^{-3}
Temperature (below Doppler Limit)	10 μK
Phase Space Density $\rho\Lambda^3$	10^{-6}

TEMPERATURE MEASUREMENTS



HOW COLD CAN WE GET?

Spontaneous emission causes heating,

due to randomly distributed emission.

stationary state when
heating rate=cooling rate minimal,

when

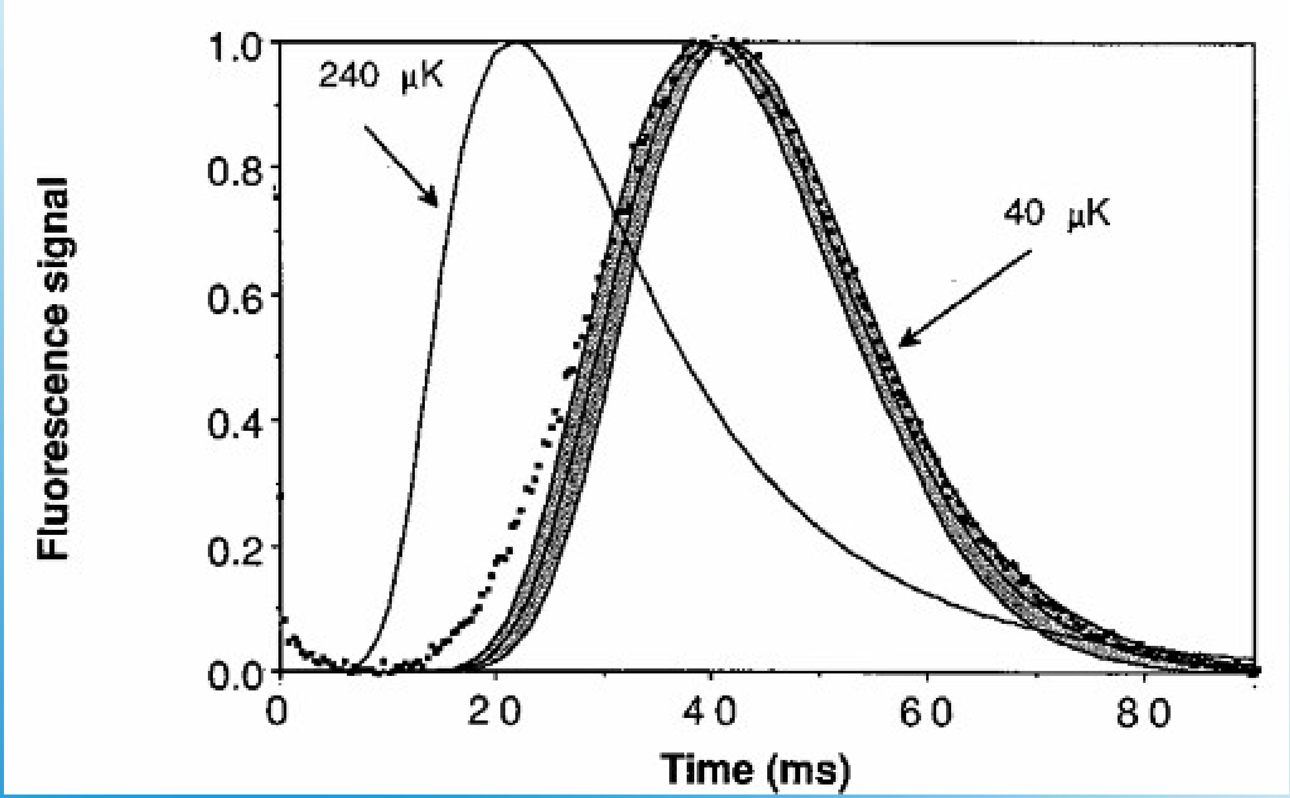
$$\delta = -\gamma/2 \rightarrow E_{kin,min} = \hbar\gamma/2$$

$$\mathbf{T = \hbar\gamma/2k_B}$$

$\gamma \approx$ a few MHz $\rightarrow$ T_{min} typically 0.1…0.25 mK

Prediction by Hänsch, Schawlow, Wineland, Dehmelt (1975)

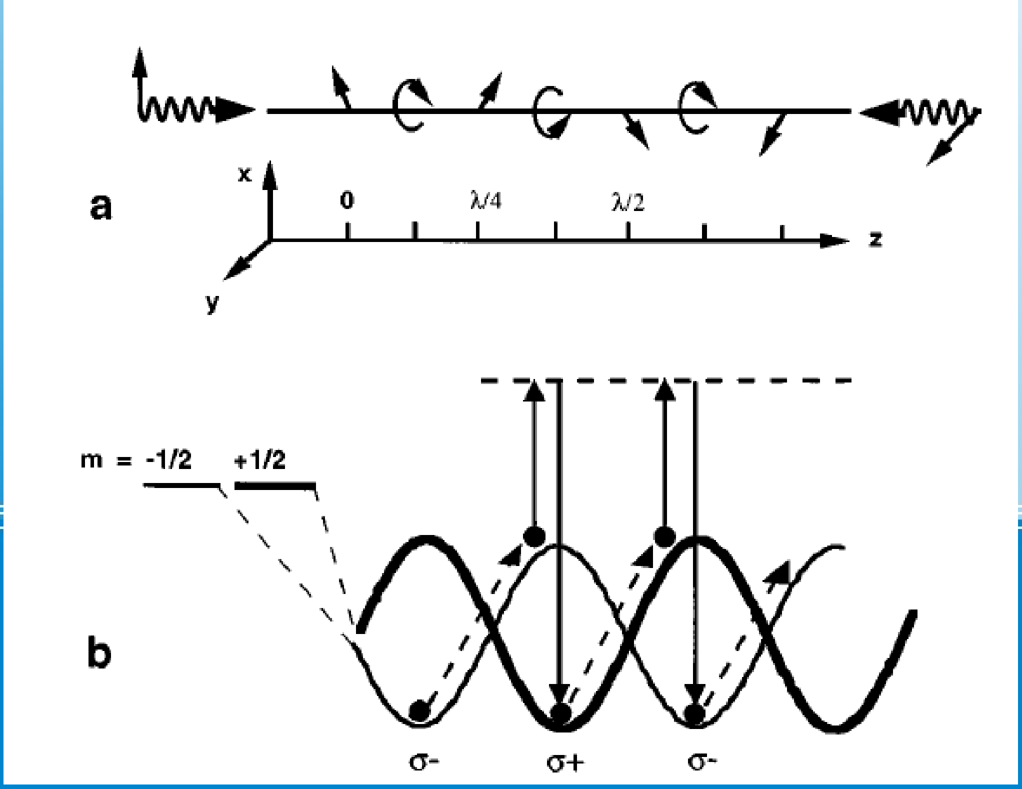
MUCH LOWER TEMPERATURES OBSERVED!!



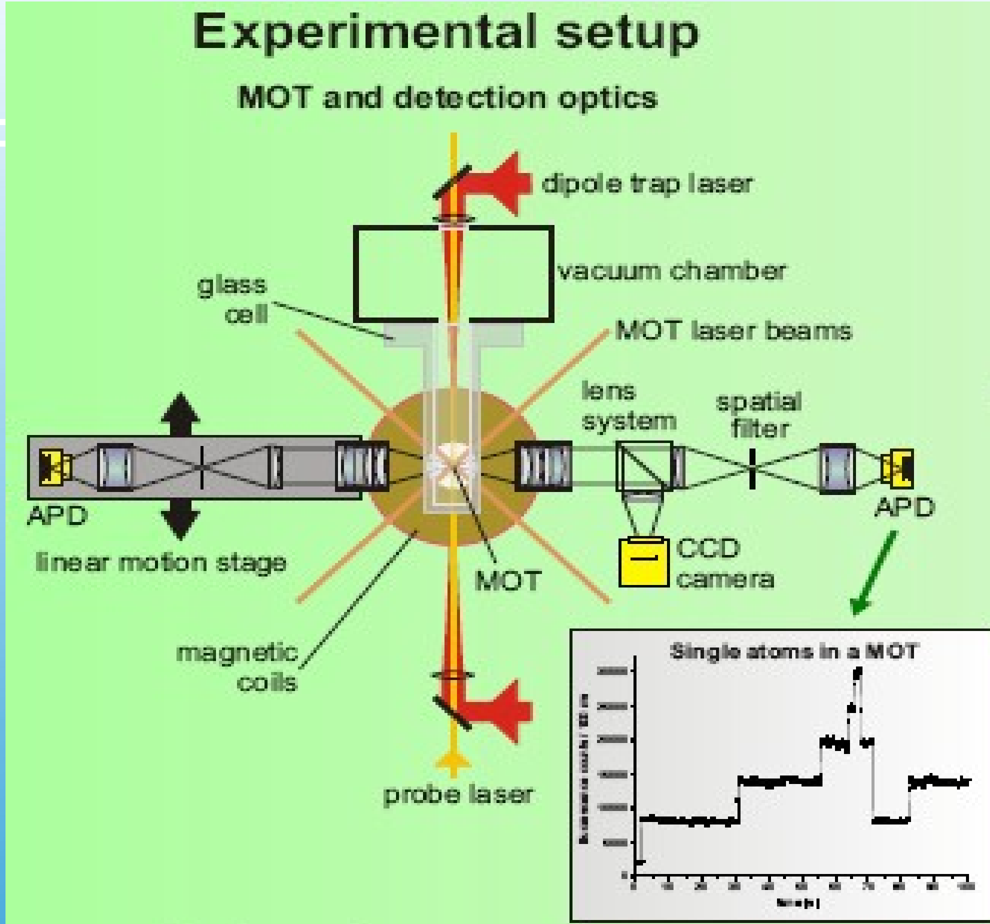
SISYPHUS COOLING

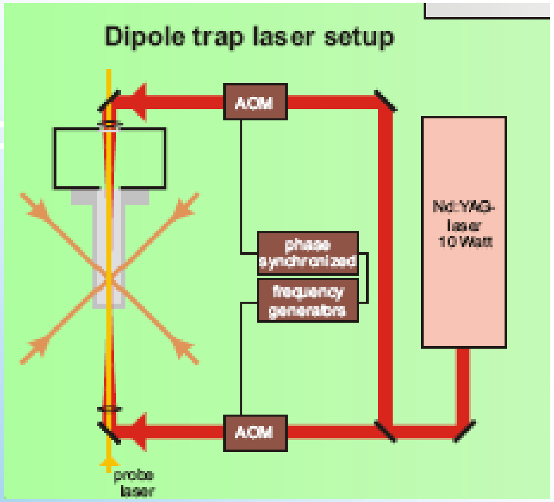
- Light shift on Zeeman level
  (Clebsch Gordan coefficients)

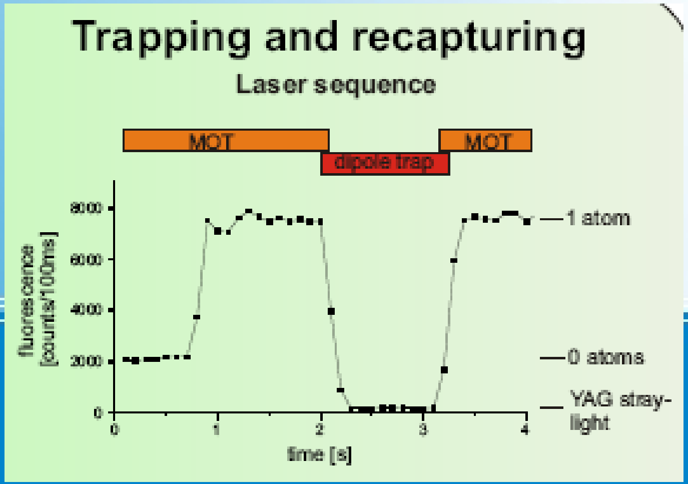
Counter propagating Laser beams with orthogonal polarization create a polarization grating:



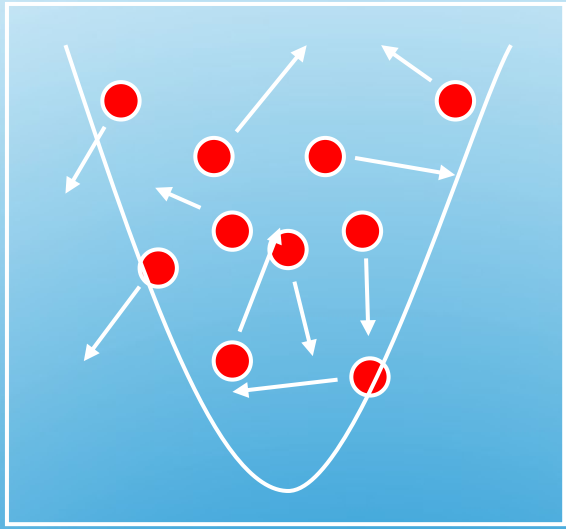
SINGLE ATOM TRAPS

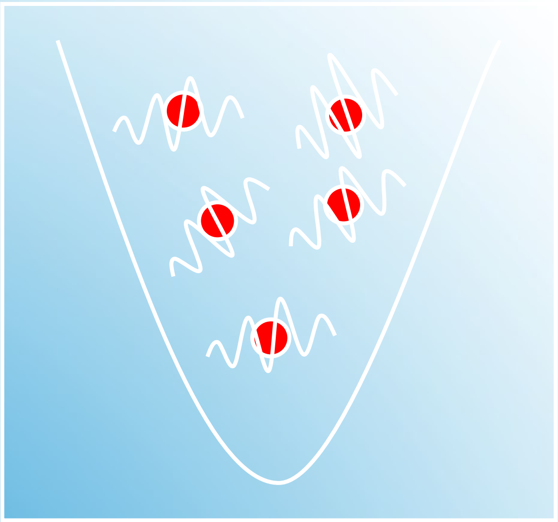






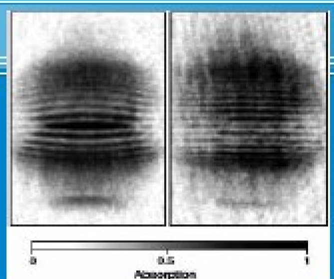
WHAT IS AN ULTRACOLD QUANTUM GAS?

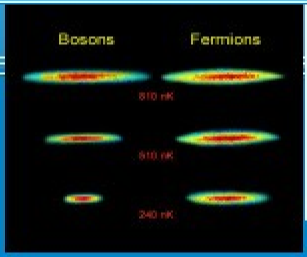


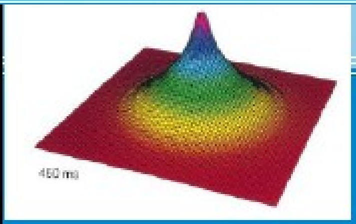


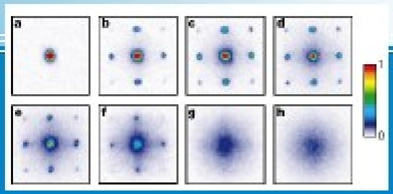
$$\Lambda_{dB} = \sqrt{\frac{h^2}{2\pi m k_B T}}$$

Gas shows "quantum" effects when the wave packets start to overlap





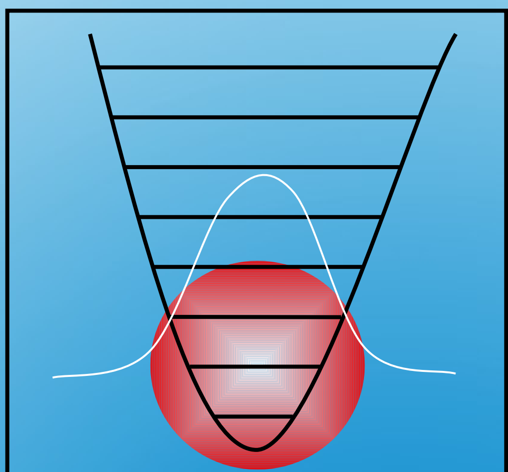




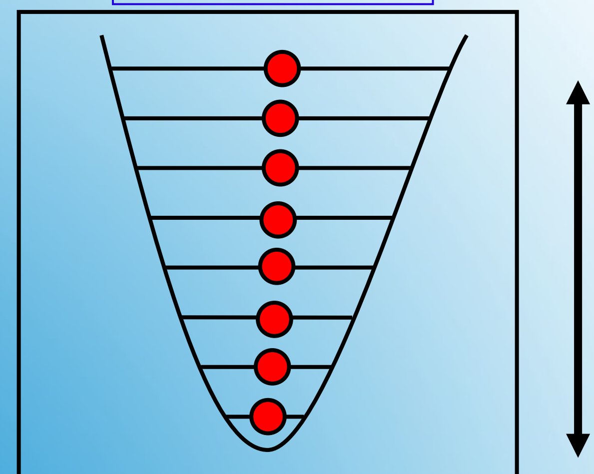
FERMIONS AND BOSONS

At zero temperature ....

Bosons



Fermions



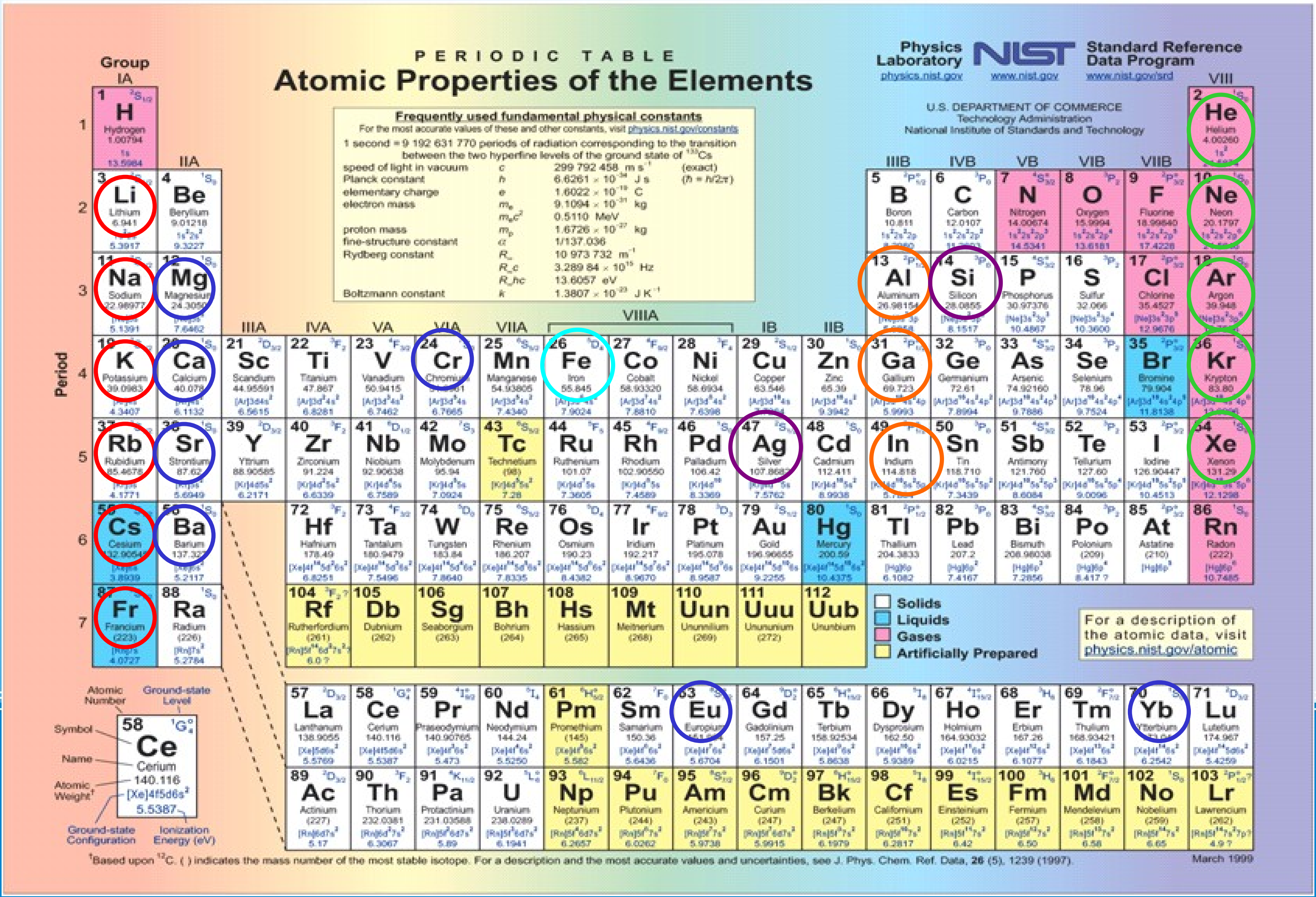
Fermi energy

$E_F = k_B T_F$

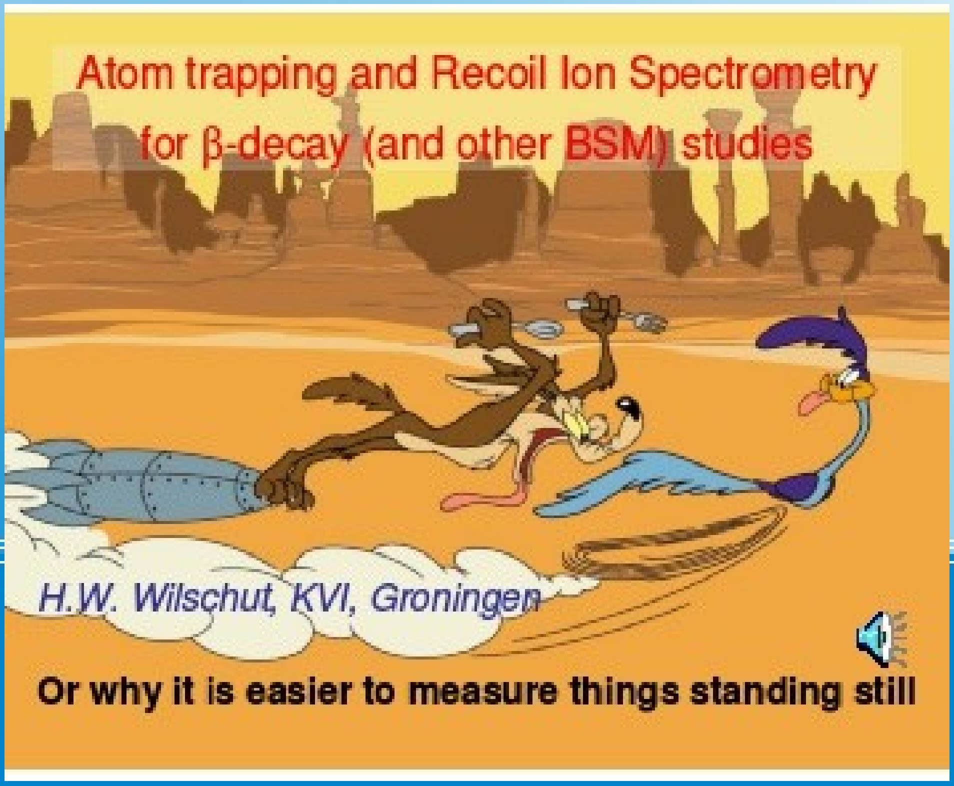
Bose-Einstein condensation

Degenerate Fermi gas

Laser cooling : demonstrated species



RADIOACTIVE ATOM TRAPPING



WHY TO TRAP RADIOACTIVE ATOMS?

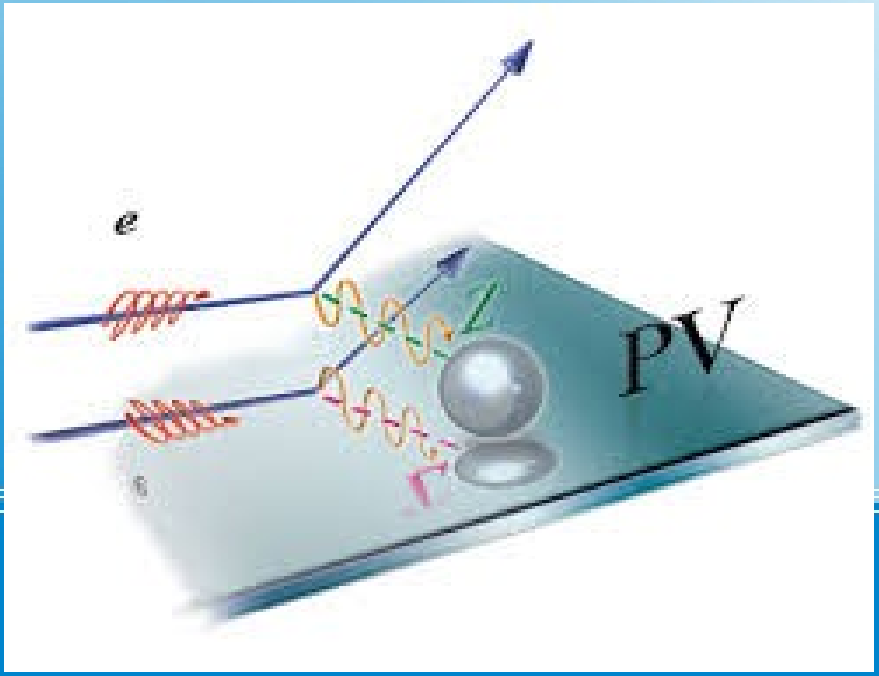
A) BECAUSE IT IS A WAY OF STUDYING NUCLEAR PHYSICS AND FUNDAMENTAL PROCESSES BY ATOMIC PHYSICS TOOLS

→ **β DECAY**
→ **ATOMIC PARITY NON CONSERVATION**
  → **STANDARD MODEL CHECK**

B) BECAUSE IT BECOMES POSSIBLE TO PERFORM SPECTROSCOPY ON RARE SPECIES

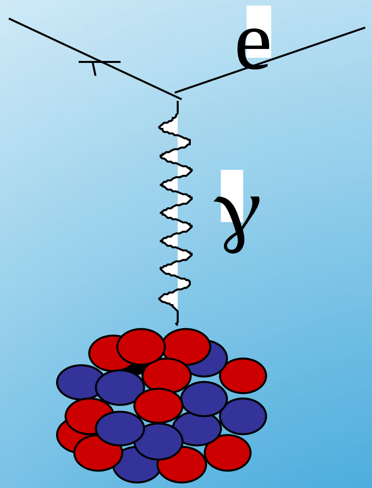
FRAP/TRAPRAD/FRANCIUM/WADE +
BERKELEY, LOS ALAMOS, TISOL, STONY BROOK, KVI,
TRIUMPH, CYRIC

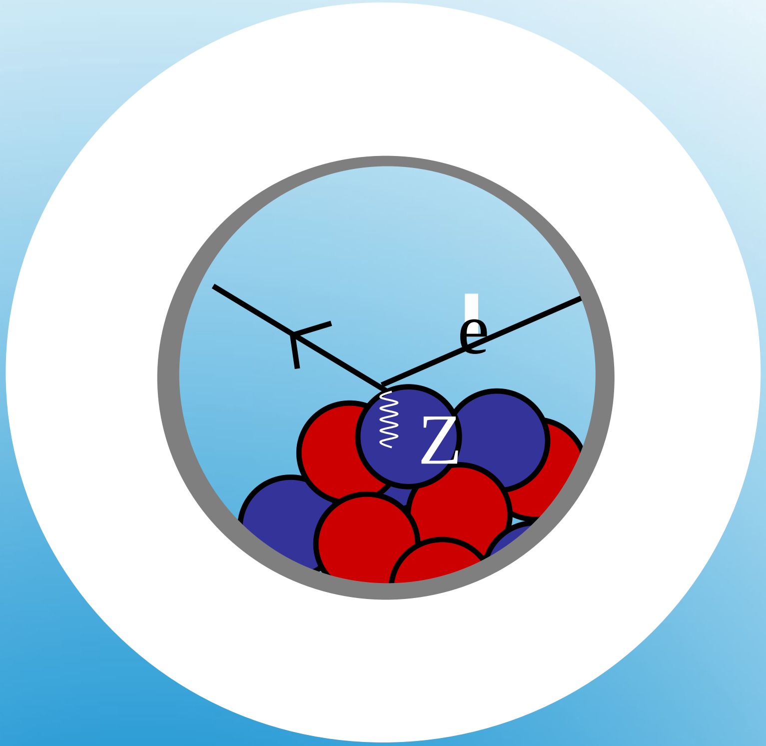
ATOMIC PARITY NON CONSERVATION



Atomic parity violation

RELEVANT ELECTRON - HADRON PROCESSES





$$A_{em} \propto \frac{e^2}{p^2}$$

$$A_W \propto \frac{e^2}{p^2 + M_{Z_0}^2 c^2}$$

p is the momentum transfer
(inversely proportional to the Bohr radius)

$$p \sim m_e \alpha c$$

Atomic parity violation

Different transition probabilities for two mirror - image experiments

The amplitude A_W contains a part that is odd under space reflection and gives rise to a left - right asymmetry A_{LR} by interference with A_{em}.

$$P_{L/R} = \left| A_{em} \pm A_W^{odd} \right|^2$$

$$A_{LR} = \frac{P_L - P_R}{P_L + P_R} \simeq 2\mathrm{Re}\frac{A_W^{odd}}{A_{em}}$$

$$\alpha^2 \left(\frac{m_{e^-}}{M_{Z_0}} \right)^2 \sim 10^{-15}$$

Atomic parity violation

Completely hopeless? No!

There are 2 factors of enhancement:

A. The so - called Z^3 law

- For valence electrons belonging to penetrating orbitals, the orbitals are deformed in the vicinity of the nucleus, where electrons "see" a Coulomb potential generated by a charge Ze. The orbital radius is given by a_0/Z, in such a way that p^2 is enhanced by Z^2.
- The various nucleons add for their contributions coherently: the number of nucleons grows as Z

Atomic parity violation

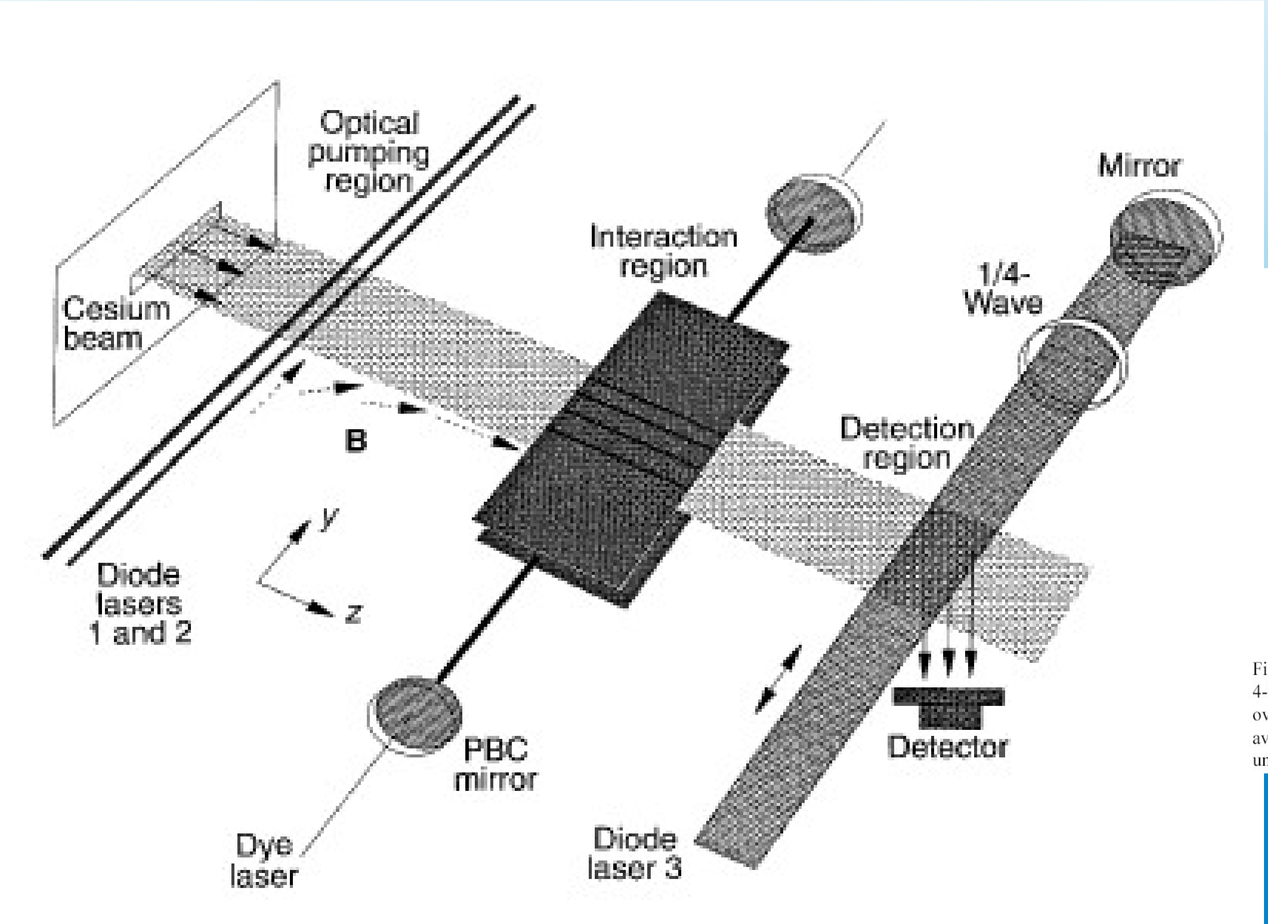
B. The second source comes from the possibility of exciting highly forbidden transitions like $nS_{1/2} \rightarrow (n+1)S_{1/2}$ in alkalis. The electromagnetic selection rules strictly forbid the electric dipole transition; dipole magnetic transitions M_1 are allowed by the symmetry, not by the change in radial number.

The weak interaction associated with the boson exchange breaks this rule and gives rise to a parity violating electric dipole amplitude $E^{(PV)}_1$:

$$Im\, E_1^{pv}/M_1 \simeq 0.5 \times 10^{-4}$$

Cs MEASUREMENTS

To obtain an observable that is first order in the APNC amplitude, it is possible to apply a dc electric field E that also mixes S and P states. This field gives rise to a "Stark induced" E1 transition amplitude that is typically 10^5 times larger than APNC and can interfere with it.



$$R \propto \left|A_{Stark} + e^{i\theta} E_1^{APNC}\right|^2$$
$$\propto \quad A_{Stark}^2 + k A_{Stark} Im(E_1^{APNC})$$

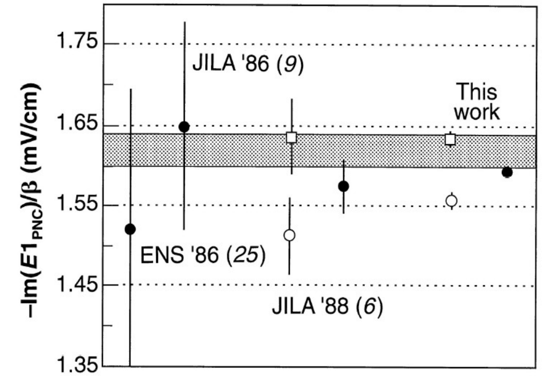


Figure 4. Historical comparison of cesium PNC results. The squares are values for the 4-3 transition, the open circles are the 3-4 transition, and the solid circles are averages over the hyperfine transitions. The band is the standard-model prediction for the average, including radiative corrections. The ±1σ width shown is dominated by the uncertainty of the atomic structure.

C.S.Wood et al.,

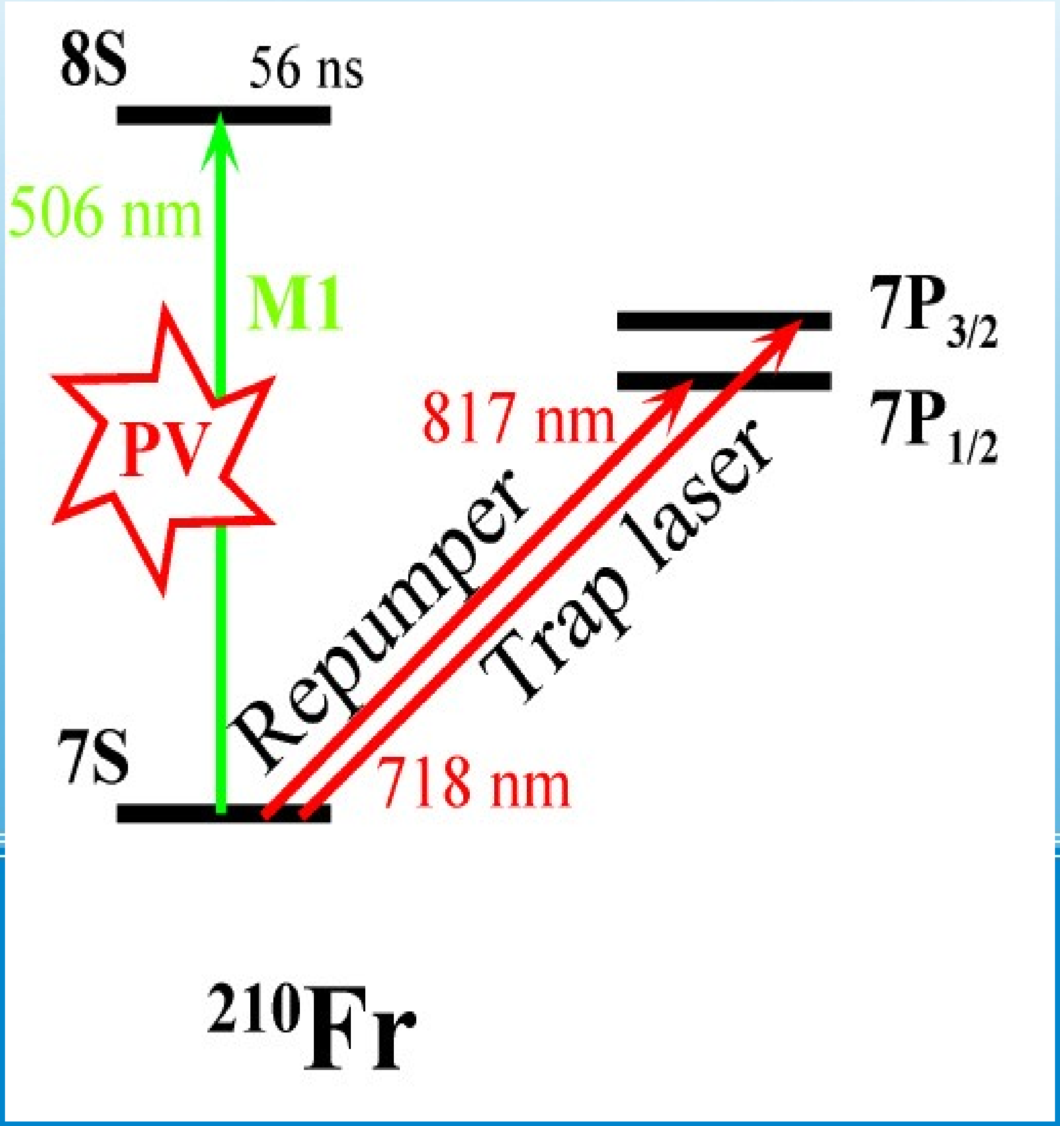
Science 275(1997)1759

Atomic parity violation

A possible experimental approach:

1. Capture Fr atoms in a MOT
2. Accumulate and cool in the MOT
3. Transfer to a second trap (purely optical)
4. Establish a "coordinate system" by dc electric field, dc magnetic field, k vector of the exciting laser
5. Excite 7S to 8S using a build up cavity and detect using the 7S to 7P transition.
6. Reverse the coordinate axis.
7. Change isotope.

“Towards” APV measurement



preliminary measure
of the ratios
α/β, β/M_1 ï M_1/M_1^{hf}
in the MOT cloud
to “calibrate” APV

Expected signal to noise ratio

- Fr production rate in Legnaro: up to 10^6 ions/s.
- Trapping efficiency $\sim 10^{-2} \Rightarrow N = 10000$ atoms in 1 mm^3 (0.01 mm^3) (optical dipole trap).
- **Laser intensity: 100 mW/mm^2**, enhanced by a factor $\zeta = 1000$ with a Fabry-Perot cavity (cf. Boulder) $\Rightarrow P/S = 10$ kW/cm^2.
- Fluorescence detection efficiency: $\eta \sim 10\%$.

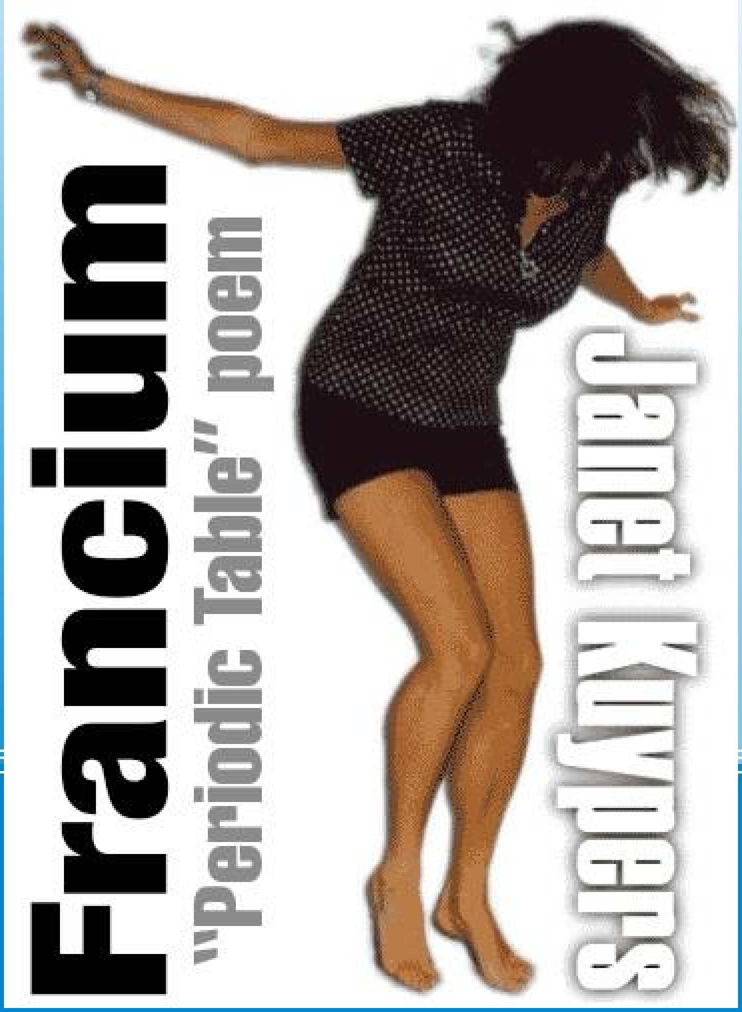
$$S/N = \Im m E_1^{pv} \sqrt{\frac{4\pi}{3\hbar c} \frac{1}{\hbar \Gamma} \frac{P}{S}} \eta N \sqrt{t} = 0.009 \sqrt{t(s)} \quad \text{(1 for t = 3 hours)}$$

How can we improve S/N ?

- Higher laser power, BUT: – heating due to photon scattering
  – photoioinization from $8S$ and $7P$.
- Higher Fr^+ Rate: $\geq 4 \cdot 10^9$ ions/s at the ISOLDE facility.
  $\Rightarrow S/N = \mathbf{0.55} \sqrt{t(\mathrm{s})}$

In 9 hours we can get $S/N = 100$

THE "TRAPRAD/FRANCIUM/WADE" EXPERIMENT



The "traprad" /"francium"/"wade" collaboration

Ferrara University and INFN:
R.Calabrese, (H.Arikawa), (S.N.Atutov), (T.Ishikawa), (G.Mazzocca), (Z.Peshev), (G.Stancari), L.Tomassetti

Legnaro National Laboratories INFN:
L.Corradi, A.Dainelli

Pisa University:
(P.Minguzzi), (S.Sanguinetti), M.L.Chiofalo

Siena University:
E.Mariotti, S. Agustsson, Y.Aoki, G.Bianchi, (V.Coppolaro), (C.de Mauro), (K.Kato), A.Khanbekyan, C.Marinelli, (L.Marmugi), (L.Moi), (N. Papi), A. Vanella, (S.Veronesi)

University College London:
Ferruccio Renzoni

Trento University:
Leonardo Ricci

(Bad) facts about francium

	Mass no. (*A*)	Half-life
Fr	202	0.34 s
	203	0.55 s
	205	3.85 s
	206	15.9 s
	207	14.8 s
	209	50 s
	211	3.1 min
	213	34.6 s
	220	27.4 s
	223	21.8 min
	224	3.3 min
Fr	225	4.0 min
	226	48 s
	227	2.47 min
	228	39 s
	230	19.1 s
	232	5 s

Fr has no stable isotopes

The longest lifetime is 22min

There is at most a tea spoon of francium in the whole Earth at any given time

⇒ continuos production and trapping for further studies is necessary

$^{210}Fr \rightarrow 3.2$ min

Facts about francium

-First spectroscopy measurements at CERN (ISOLDE):

A = 208-213, 220-228

S. Liberman *et al.*, C. R. Acad. Sci. Ser. B **286**, 253 (1978).
Francium is produced by spallation reactions in Th or U Carbide targets bombarded with protons: 10^9 **Fr/s**.

-Francium Magneto-Optical Trap (MOT):

J.E. Simsarian *et al.*, PRL **76**, 003522 (1996). (STONY-BROOK) A = 210
S.N. Atutov *et al.*, JOSA B **20**, 953 (2003). (LEGNARO) A = 209-211
Nuclear fusion-evaporation reactions in a Au target: 10^6 **Fr/s**.

Z.-T. Lu *et al.*, PRL **79**, 994 (1997). (Boulder/Berkeley)
Radioactive source: Francium produced in the decay chain
$^{229}\mathrm{Th} \rightarrow {}^{225}\mathrm{Ra} \rightarrow {}^{225}\mathrm{Ac} \rightarrow {}^{221}\mathrm{Fr} \Rightarrow 10^4$ **Fr/s**.

Commissioning of the Francium Trapping Facility at TRIUMF

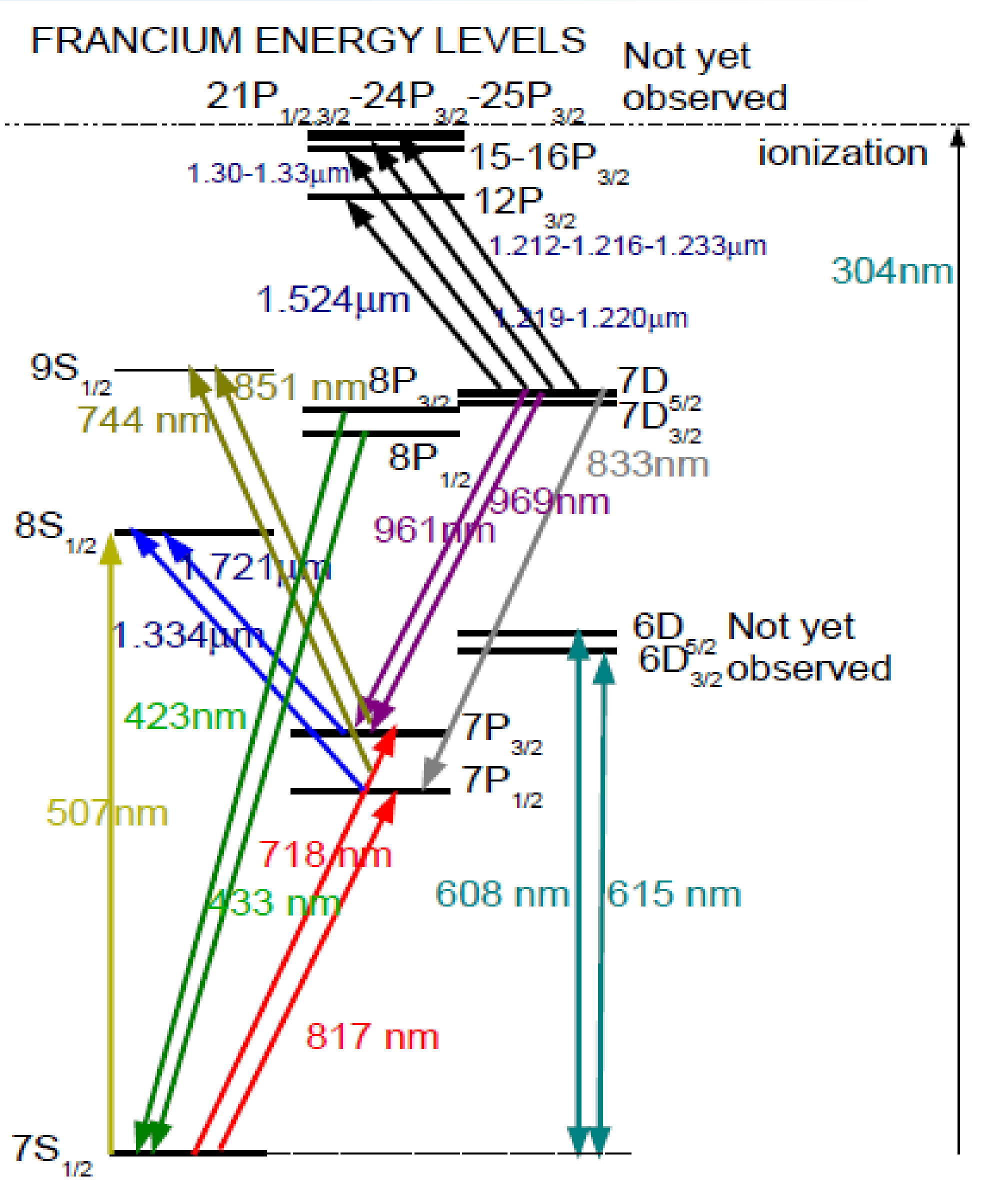
M. Tandecki et al (Submitted on 12 Dec 2013) A = 207, 209, 221

Decay-Assisted Laser Spectroscopy of Neutron-Deficient Francium

Phys. Rev. X 4, 011055 – Published 28 March 2014

K. M. Lynch etal. A = 202-207, 218-221, 229, 231

Facts about francium



(Interesting) facts about francium

spectroscopically poorly known
"simple" electronic structure
several isotopes suitable for trapping
enhanced P and T violations (Z=87)

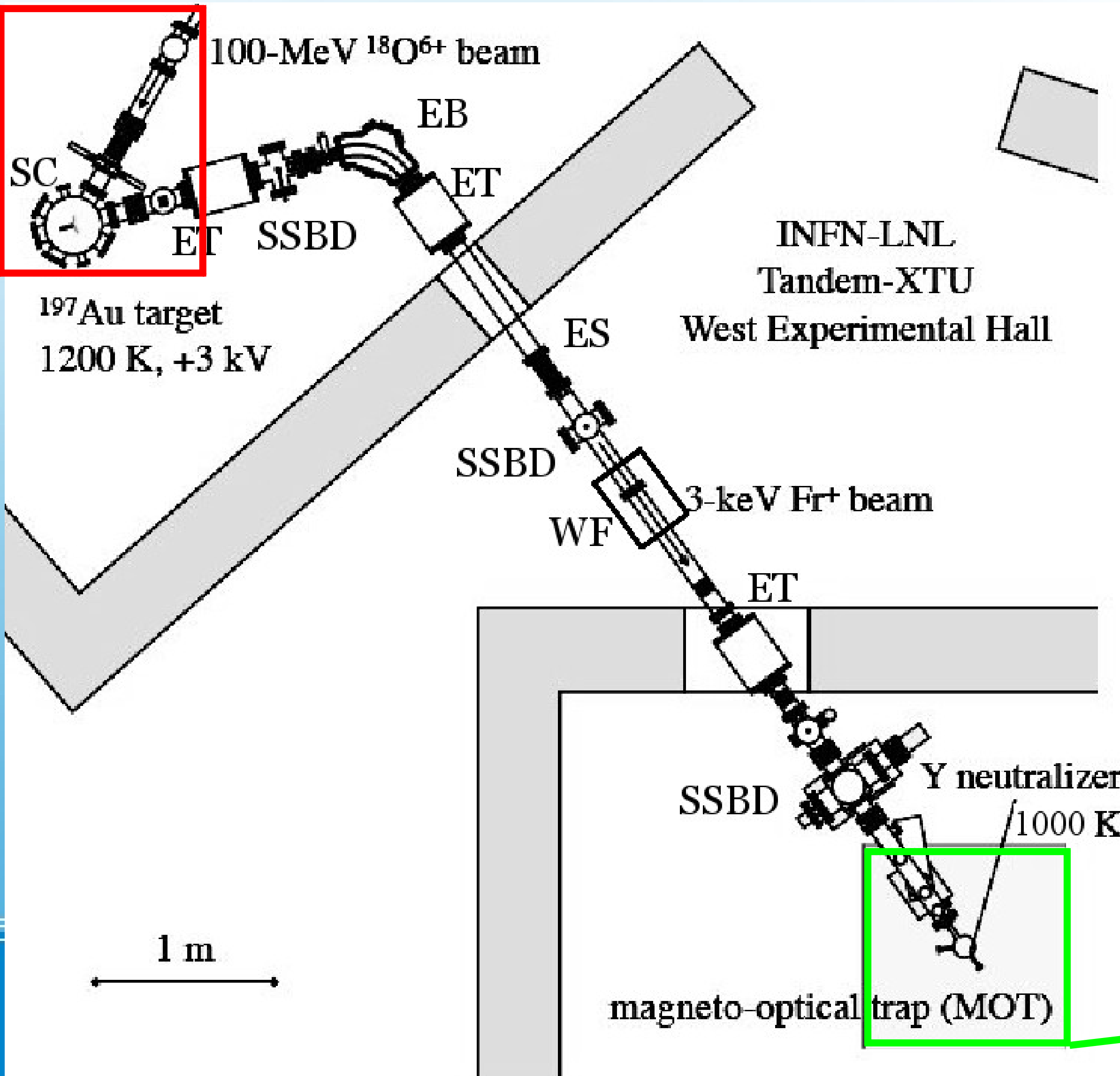
⇓

Parity Violation for the 7S – 8S transition:
test of neutral weak interactions

Parity Violation for the ground state hyperfine atomic transition: measurement of Nuclear Anapole Moment (TRIUMF/ISAC, production rate 10^{10} Fr/s, trap number 10^{7} Fr)

Search for permanent Electric Dipole Moment:
test of Time reversal violation and SUSY
(RNCP @Sendai, trap number 10^{8} Fr)

The "traprad"/"francium"/"wade" experiment



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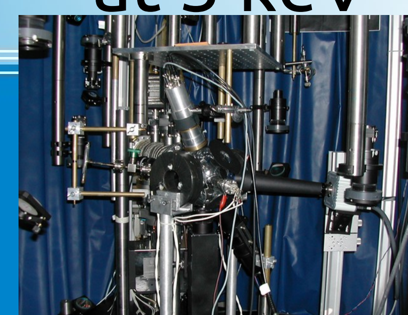
IN SUPREMÆ DIGNITATIS 1343

INFN L.N.L.

Fr production

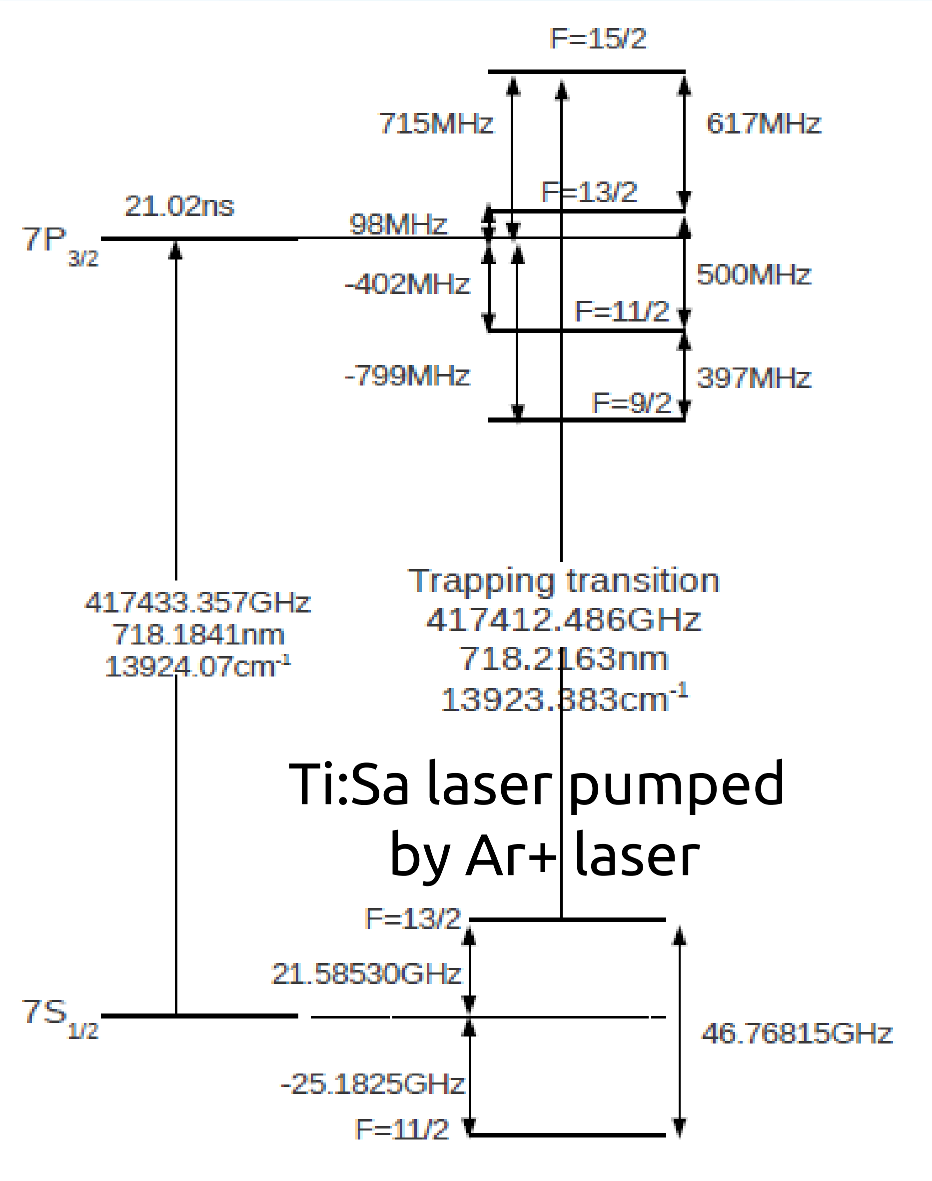
$^{197}Au + ^{18}O \rightarrow xn + ^{215-x}Fr$

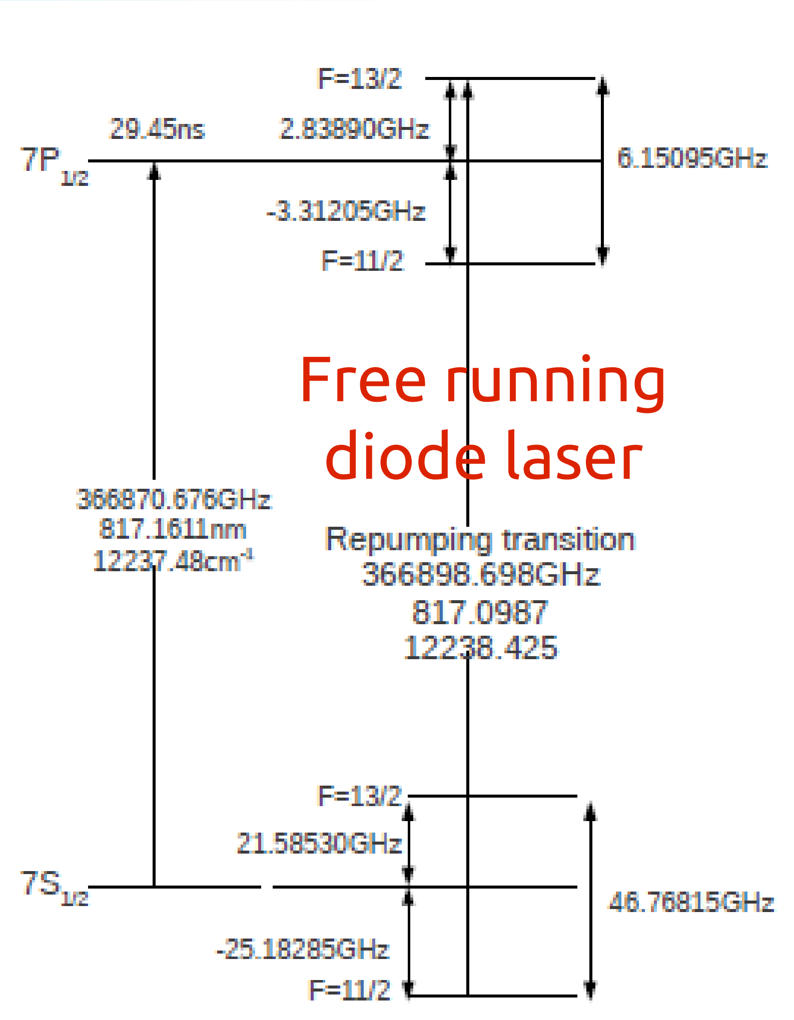
Fr^{+} (and Rb^{+}) ions transport at 3 keV



Eur Phys J ST 150 389 (2007)

The trapping and repumping transitions





The MOT cell

$\phi_{Au} = 5.1$ eV

$\phi_Y = 3.1$ eV

$I = 4.1$ eV

$$\frac{n_+}{n_a} = \frac{g_+}{g_a} \exp\left(\frac{\phi - I}{k_B T}\right)$$

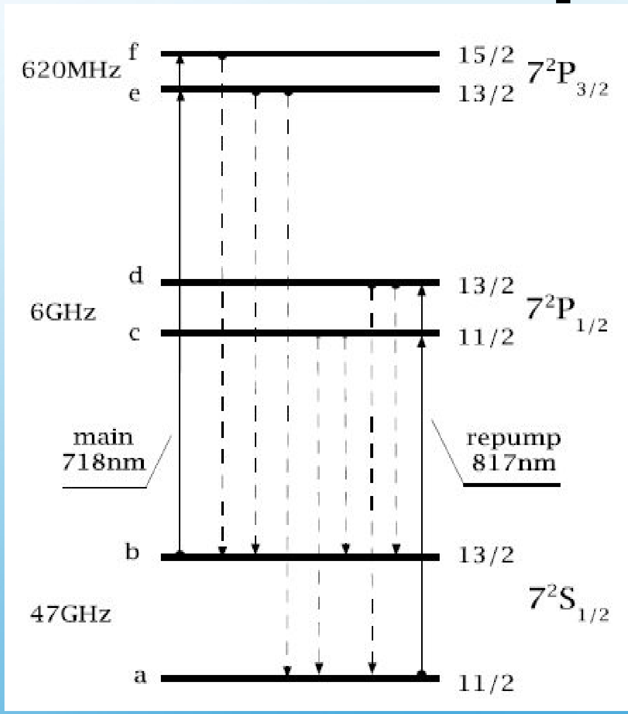
CCD Detection of the MOT

we locate a dark region behind the MOT

background subtraction:
uniform image

weighted background subtraction: compensation for laser intensity fluctuations

Calibration power-number of atoms



$$H = \hbar \begin{pmatrix} 0 & 0 & A & A & 0 & 0 \\ 0 & \omega_b & 0 & 0 & C & C \\ A^* & 0 & \omega_c & 0 & 0 & 0 \\ A^* & 0 & 0 & \omega_d & 0 & 0 \\ 0 & C^* & 0 & 0 & \omega_e & 0 \\ 0 & C^* & 0 & 0 & 0 & \omega_f \end{pmatrix}$$

$$\Gamma = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \gamma_c & 0 & 0 & 0 \\ 0 & 0 & 0 & \gamma_c & 0 & 0 \\ 0 & 0 & 0 & 0 & \gamma_f & 0 \\ 0 & 0 & 0 & 0 & 0 & \gamma_f \end{pmatrix}$$

hyp: trap laser detuning $-5\gamma_f$

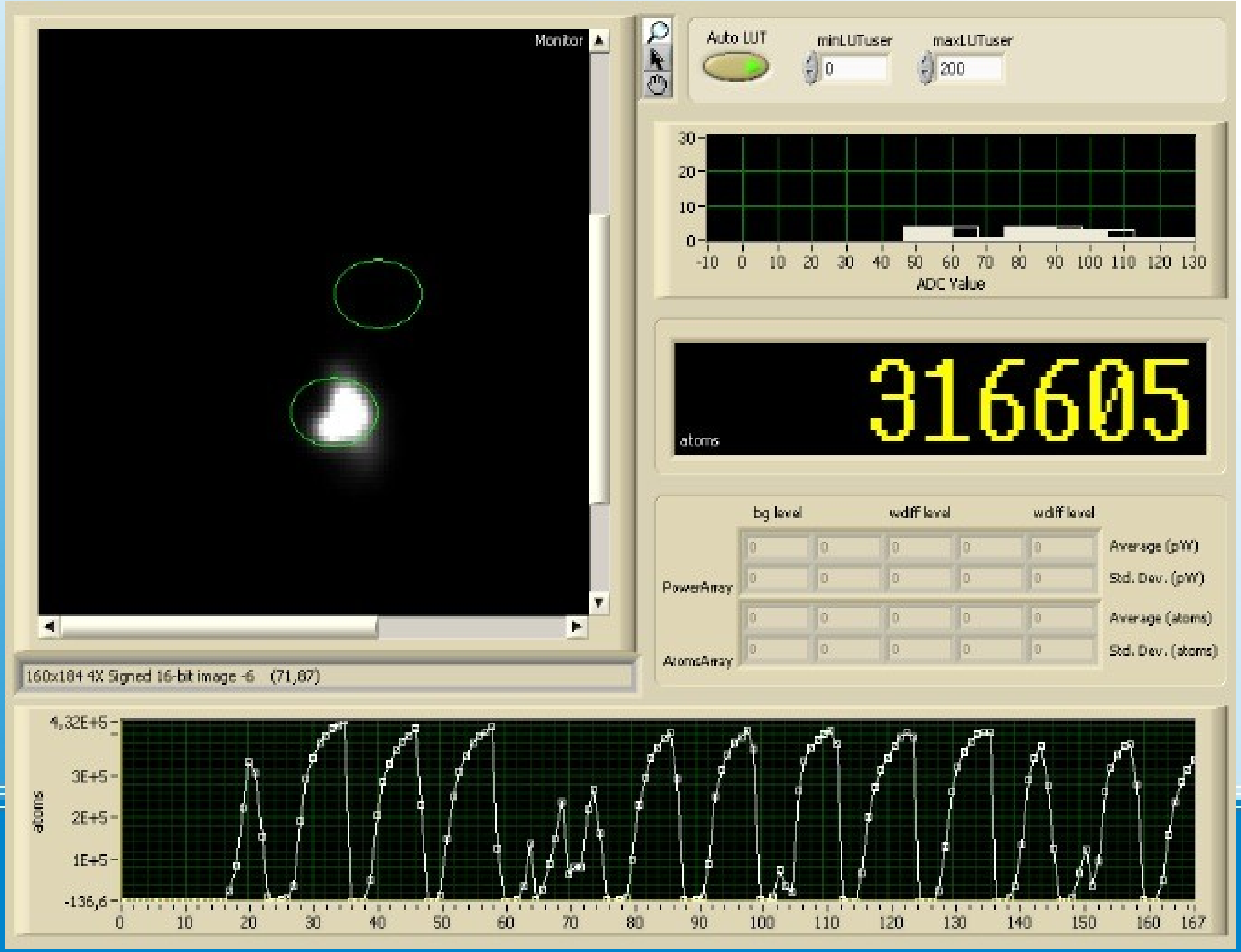
Rb: 1pW 1400 atoms

Fr: 1pW 1900 atoms

noise level less than 30 atoms

Electronic noise: 3 atoms, shot noise: 8 atoms

Tests on Rb MOT



Francium trapping

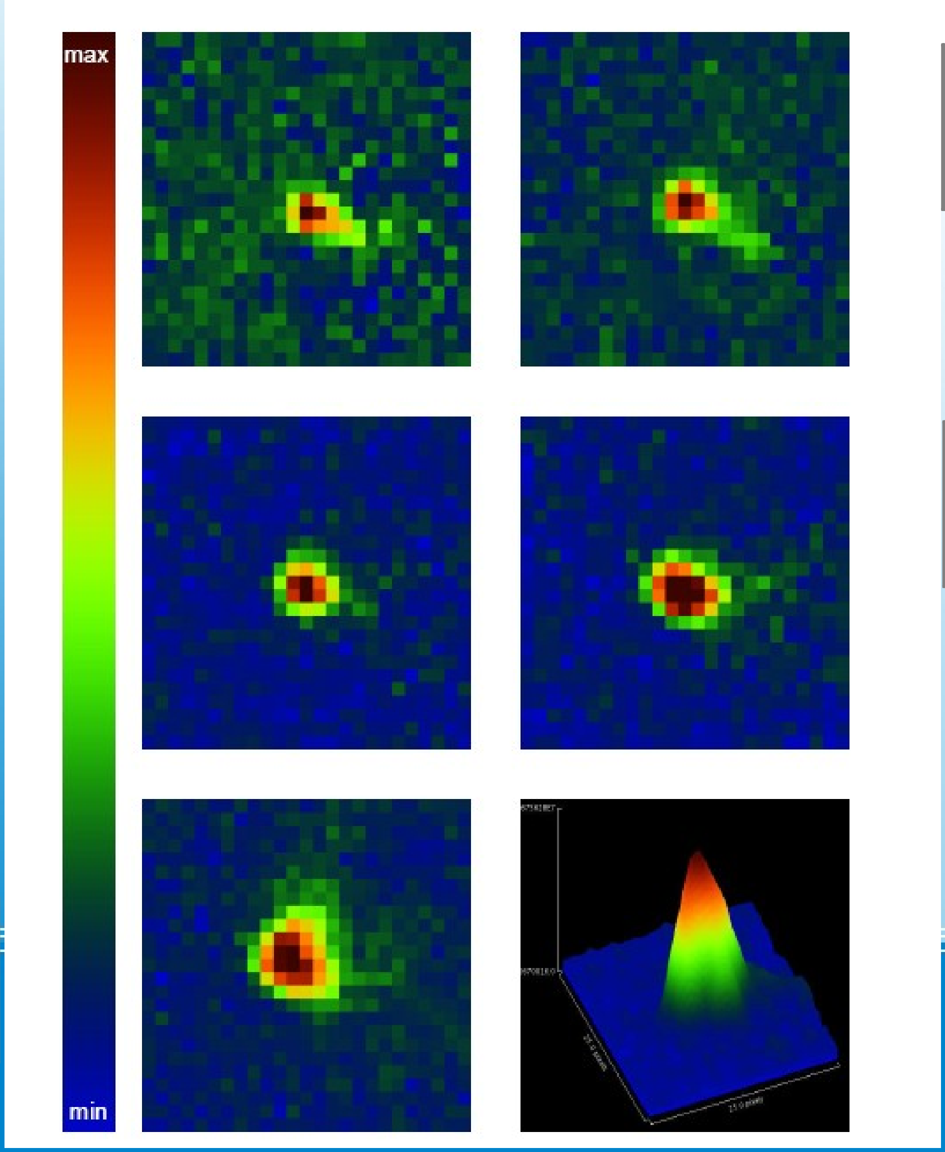
220 atoms

450 atoms

560 atoms

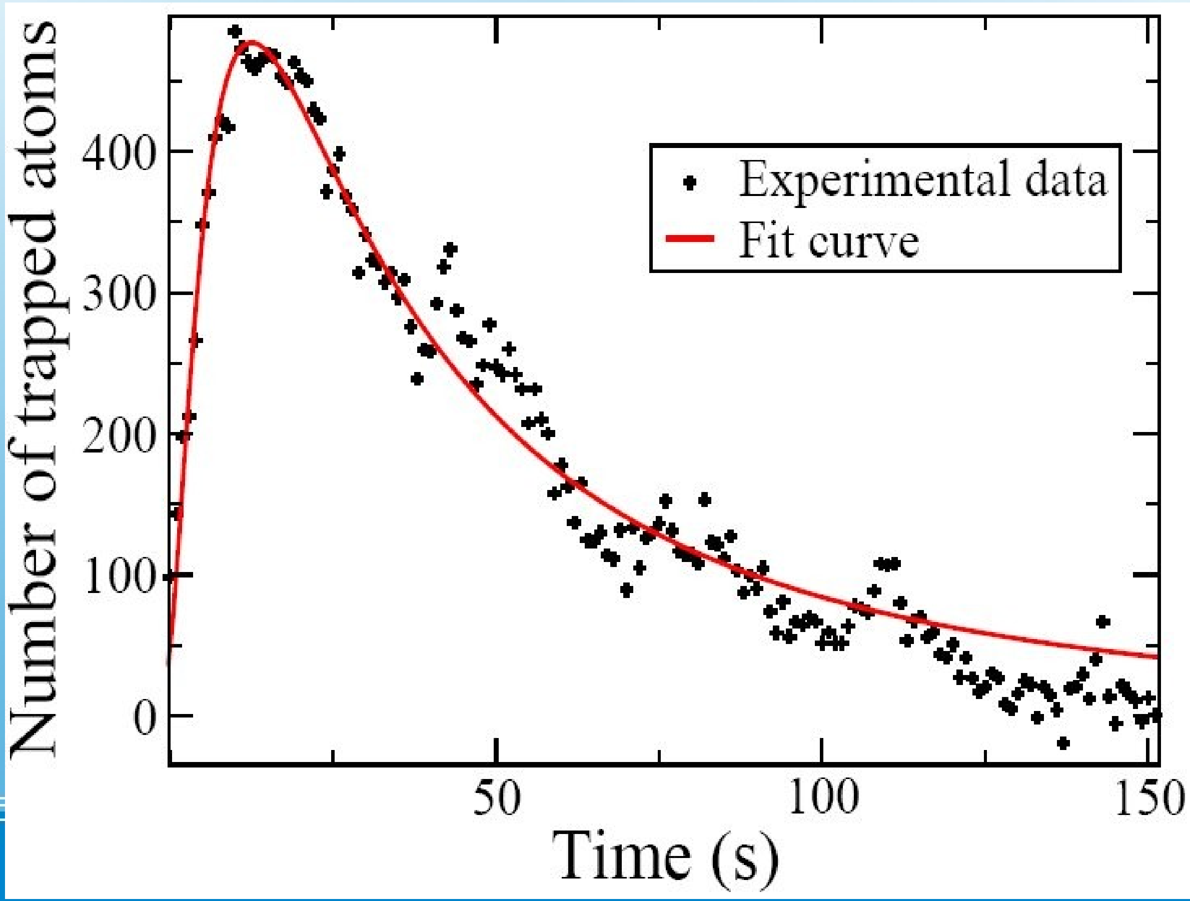
930 atoms

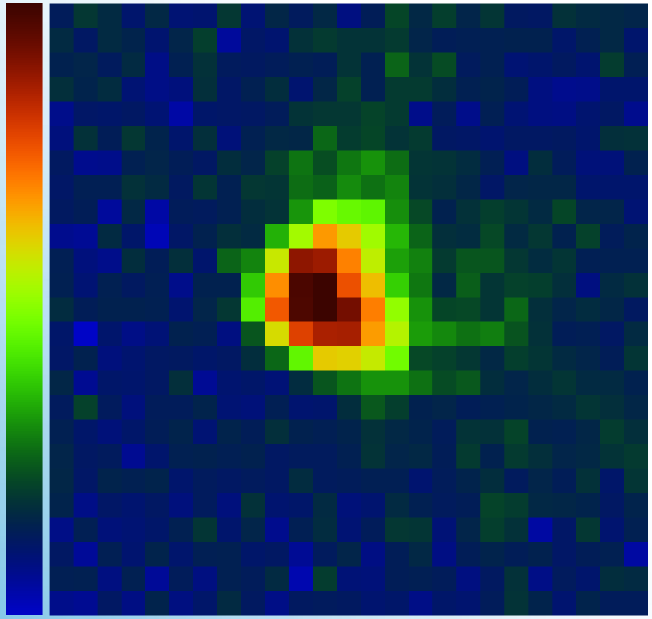
1100 atoms

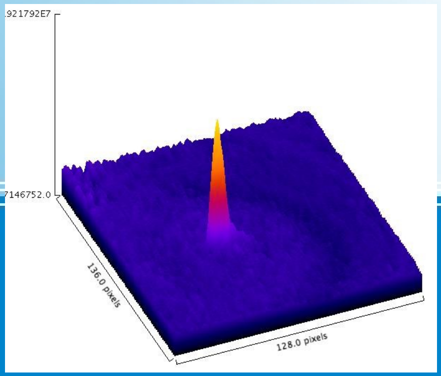


Francium trapping

accumulation in the cold yttrium and fast release
by suddenly switching on the heating of neutraliser

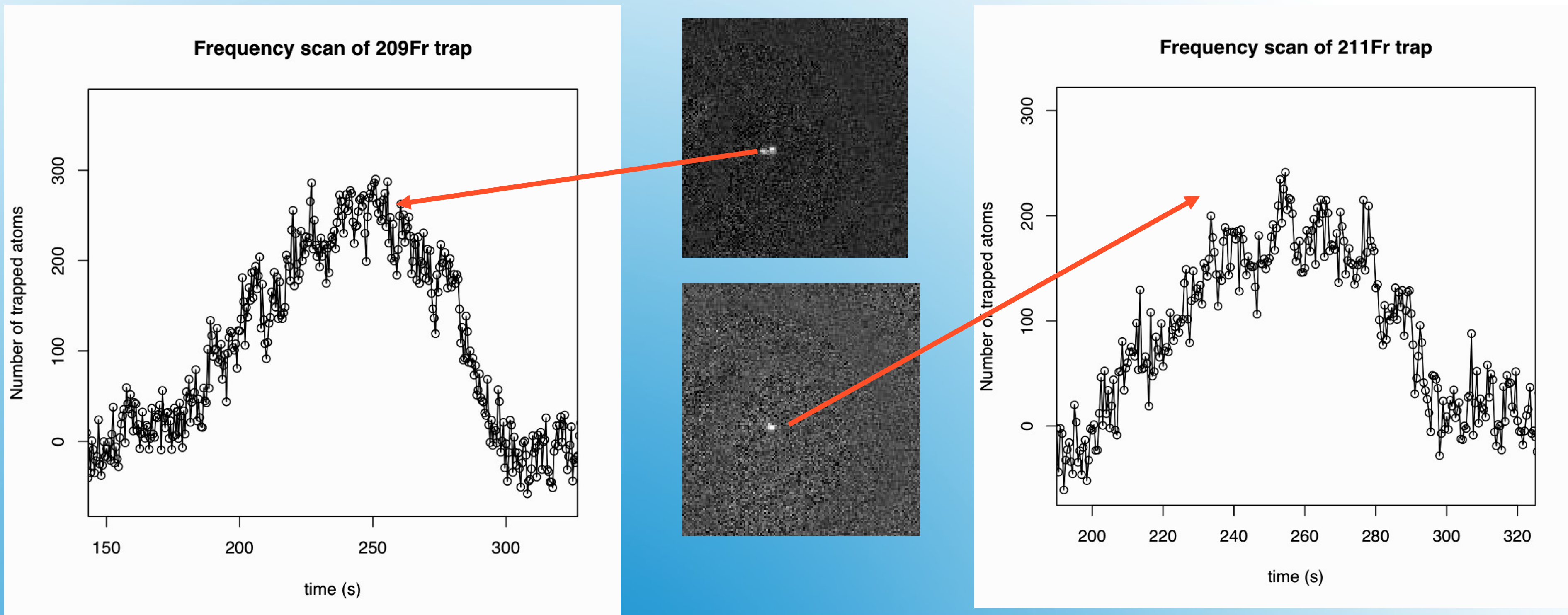






up to 10000 atoms !!

Other Fr isotopes (209, 211)



Estimate of trapping efficiency

trapping efficiency

$$\eta \equiv \frac{N_t}{I \tau_c}$$

$\eta_{209} \simeq 3{,}2 \times 10^{-4}$

$\eta_{210} \simeq 2{,}3 \times 10^{-4}$

Melting the target.....

....means to start since the beginning!
(and fight with radioprotectors)

....breaking the cell
or the neutralizer,
preparing a wrong coating,
cumulating too much Rb,
exhausting the argon tube,

....

...again means to start since the beginning!

10 days of beam time per year maximum

PRECISION MEASUREMENTS ON THE FRANCIUM LEVELS

List of atomic observables for nuclear studies

→ **Hyperfine structure**

$$\Delta E_{HFS} = \Delta E_{dipole} + \Delta E_{quadrupole}$$

$$= \frac{A}{2} C + \frac{B}{4} \frac{\frac{3}{2} C (C+1) - 2IJ (I+1)(J+1)}{IJ (2I-1)(2J-1)}$$

$$A = \frac{\mu_I B_e(0)}{JI}$$

$$B = q_e Q_S \langle \frac{\partial^2 V}{\partial z^2} \rangle$$

$$C = F(F+1) - J(J+1) - I(I+1)$$

$$\frac{A}{A'} \simeq \frac{\mu}{\mu'} \frac{I'}{I} \qquad \frac{B}{B'} \simeq \frac{Q_s}{Q_s'}$$

3682 Vol. 42, No. 18 / September 15 2017 / Optics Letters Letter

Optics Letters

Observation of $7p^2P_{3/2} \rightarrow 7d^2D$ optical transitions in 209 and 210 francium isotopes

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List of atomic observables for nuclear studies

→ **Hyperfine anomalies**

$$A = A_{point}(1+\epsilon_{BR})(1+\epsilon_{BW})$$

$$\frac{A}{A'} = \frac{A_{\text{point}}\,(1+\epsilon_{\text{BW}})\,(1+\epsilon_{\text{BR}})}{A'_{\text{point}}\,(1+\epsilon'_{\text{BW}})\,(1+\epsilon'_{\text{BR}})} \approx \frac{\mu I'}{\mu' I}\left(1 + {}^{A}\Delta^{A'}\right)$$

Hyperfine anomalies in Fr: boundaries of the spherical single particle model

J. Zhang (张颉颃) [1], M. Tandecki[2], R. Collister[3], S. Aubin[4], J. A. Behr[2], E. Gomez[5], G. Gwinner[3], L. A. Orozco[1], M. R. Pearson[2], and G. D. Sprouse[6]

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(Dated: July 2, 2015)

We have measured the hyperfine splitting of the $7P_{1/2}$ state at the 100 ppm level in Fr isotopes (^{206g,206m,207,209,213,221}Fr) near the closed neutron shell (N = 126 in ^{213}Fr). The measurements in five isotopes and a nuclear isomeric state of francium, combined with previous determinations of the $7S_{1/2}$ splittings, reveal the spatial distribution of the nuclear magnetization, i.e. the Bohr-Weisskopf effect. We compare our results with a simple shell model consisting of unpaired single valence nucleons orbiting a spherical nucleus, and find good agreement over a range of neutron-deficient isotopes ($^{207-213}$Fr). Also, we find near-constant proton anomalies for several even-N isotopes. This identifies a set of Fr isotopes whose nuclear structure can be understood well enough for the extraction of weak interaction parameters from parity non-conservation studies.

List of atomic observables for nuclear studies

→ **Isotope shift**

→ **Mean square nuclear charge radii**

PHYSICAL REVIEW A **90**, 052502 (2014)

Isotope shifts in francium isotopes $^{206-213}Fr$ and ^{221}Fr

R. Collister and G. Gwinner
Department of Physics and Astronomy, University of Manitoba, Winnipeg, Canada MB R3T 2N2

M. Tandecki, J. A. Behr, and M. R. Pearson
TRIUMF, Vancouver, Canada BC V6T 2A3

J. Zhang and L. A. Orozco
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S. Aubin
Department of Physics, College of William and Mary, Williamsburg, Virginia 23186, USA

E. Gomez
Instituto de Física, Universidad Autónoma de San Luis Potosí, San Luis Potosi 78290, Mexico
(FrPNC Collaboration)

(Received 4 June 2014; published 7 November 2014)

We present the isotope shifts of the $7s_{1/2}$ to $7p_{1/2}$ transition for francium isotopes $^{206-213}Fr$ with reference to ^{221}Fr collected from two experimental periods. The shifts are measured on a sample of atoms prepared within a magneto-optical trap by a fast sweep of radio-frequency sidebands applied to a carrier laser. King plot analysis, which includes literature values for $7s_{1/2}$ to $7p_{3/2}$ isotope shifts, provides a field shift constant ratio of 1.0520(10) and a difference between the specific mass shift constants of 170(100) GHz amu between the D_1 and D_2 transitions, of sufficient precision to differentiate between *ab initio* calculations.

$$\delta\nu^{A,A'} = \delta\nu^{A,A'}_{\text{mass shift}} + \delta\nu^{A,A'}_{\text{field shift}}$$

$$\delta\nu^{A,A'}_{\text{mass shift}} = \frac{m^{A'} - m^{A}}{m^{A} m^{A'}} (N + S)$$

$$\delta\nu^{A,A'}_{\text{field shift}} = \frac{Ze^2}{6h\epsilon_0} \Delta \left|\psi_e(0)\right|^2 \delta\langle r^2\rangle^{A,A'}$$

$$\langle r^2\rangle = \frac{3}{5} r_0^2 A^{\frac{2}{3}}$$

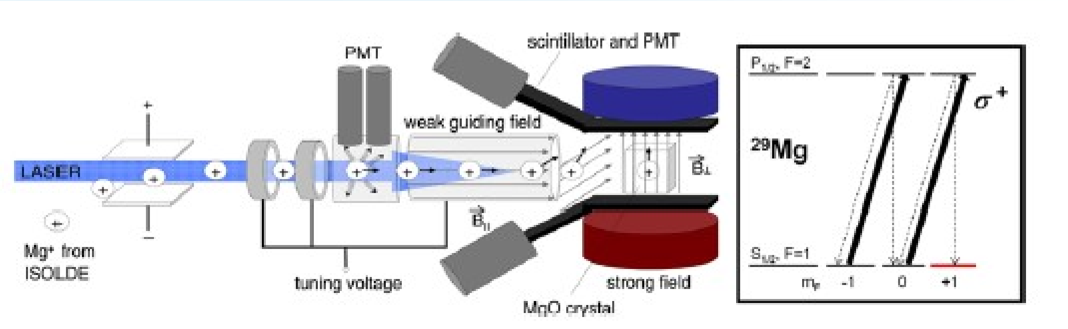
$$\langle r^2\rangle \approx \langle r^2\rangle_0 \left(1 + \frac{5}{4\pi}\langle\beta_2^2\rangle\right)$$

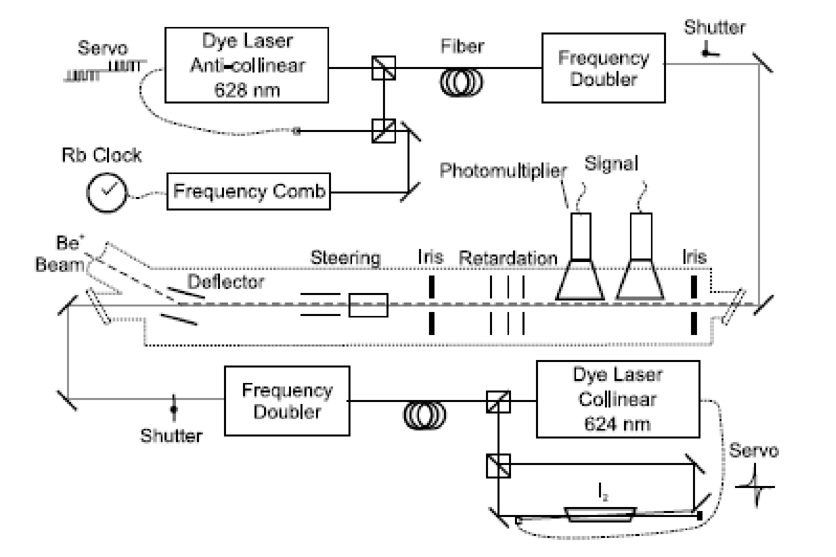
→ **Quadrupole deformation parameter**

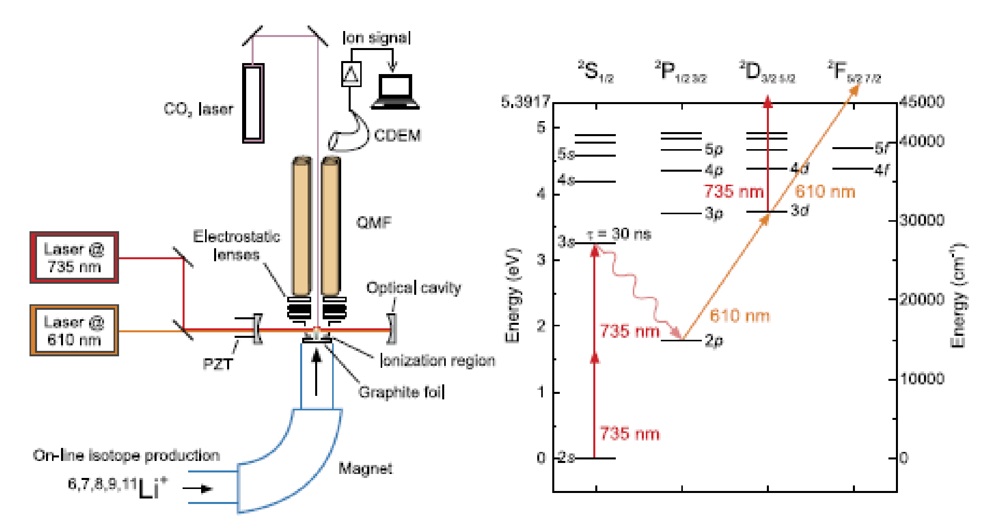
$$Q_s = \frac{3\Omega^2 - I(I+1)}{(I+1)(2I+3)} Q_0$$

$$Q_0 = \frac{3}{\sqrt{5\pi}} ZeR^2 \langle\beta_2\rangle \left(1 + 0.36\langle\beta_2\rangle\right)$$

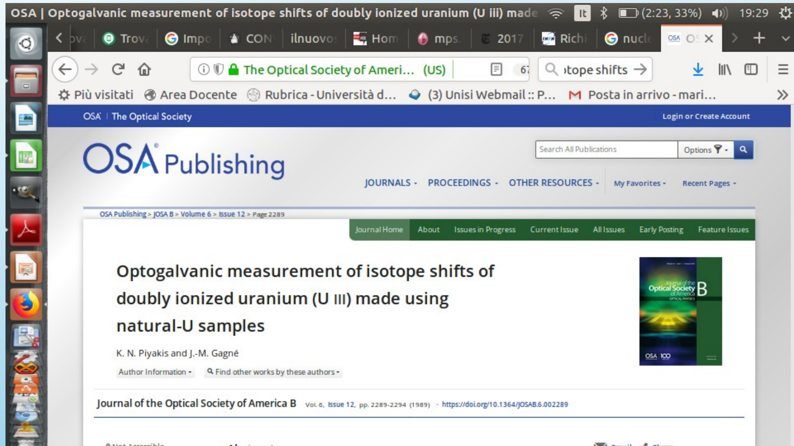
List of atomic observables for nuclear studies







List of atomic observables for nuclear studies



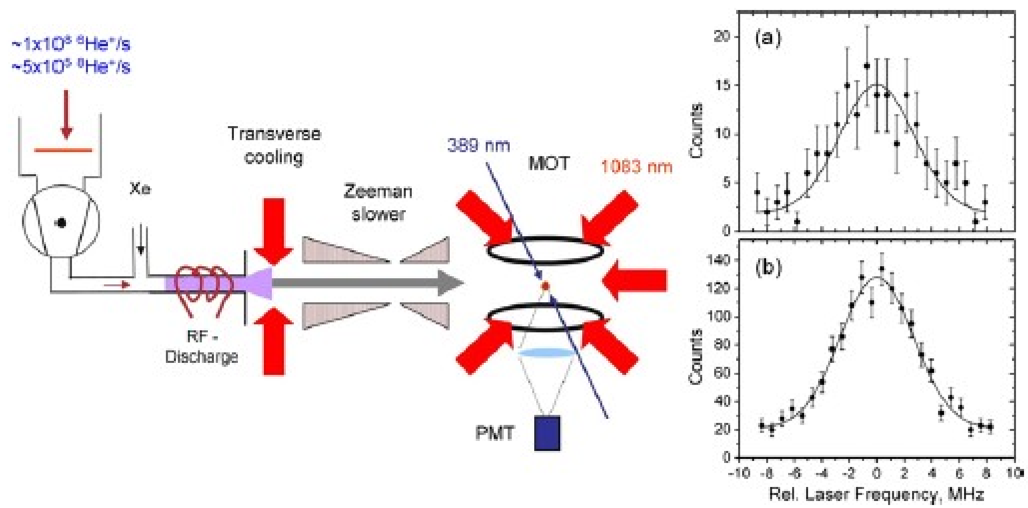
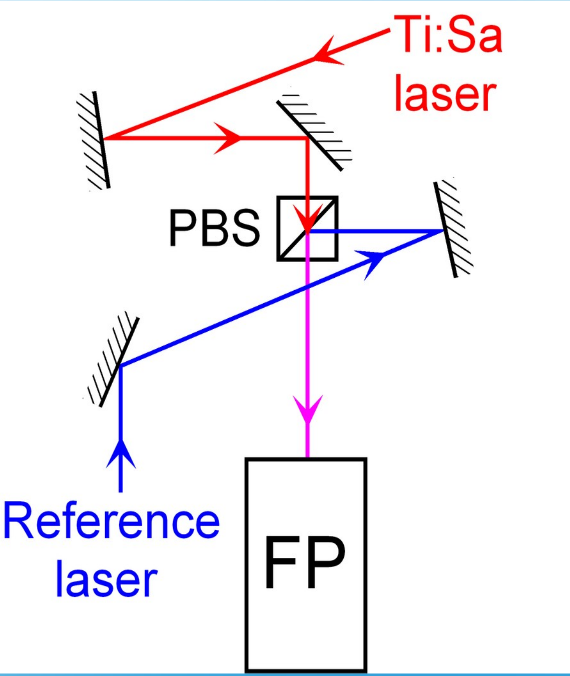


Fig. 6.8 Experimental setup for the isotope shift measurements of He isotopes (*left*) as explained in the text. The *upper plot* (a) at the *right* shows the very first spectrum recorded solely with the first ^{8}He atom in the MOT obtained within 0.4 s. The *lower figure* (b) shows an integrated spectrum over 30 atoms, resulting in a line center fitting uncertainty of 110 kHz and a $\chi^2 = 0.87$ assuming a simple Gaussian profile. Figure modified from [18], ©The Royal Swedish Academy of Sciences. Reproduced by permission of IOP Publishing. All rights reserved

Precision measurements

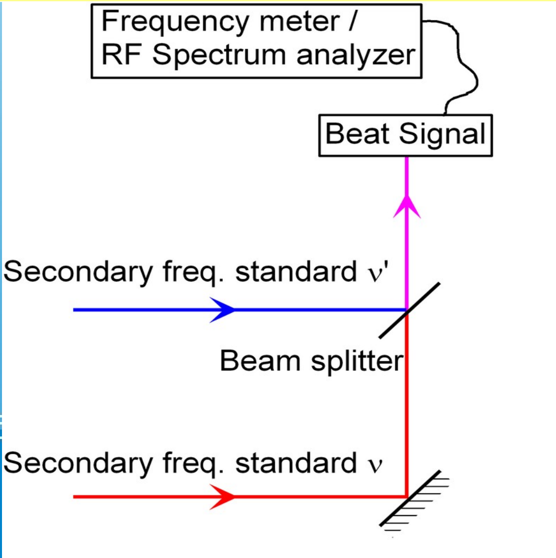
We compare the frequency of 2 lasers transmitted by a confocal FP cavity (finesse 200, FSR 2 GHz) …



$$\nu_i \cdot n(\nu_i) = \frac{c}{4d}\left(N_i - \frac{2\psi(\nu_i)}{\pi}\right), \quad i = 1, 2$$

$$\Rightarrow \nu_2\ n(\nu_2) - \nu_1\ n(\nu_1) = \frac{c}{4d}\ (N_2 - N_1)$$

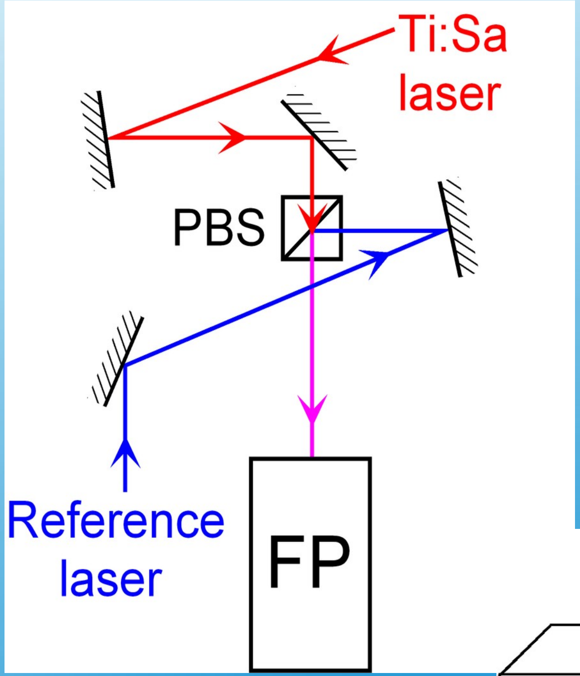
$$\nu_2\ \frac{n(\nu_2)}{n(\nu_1)} = \nu_1 + \frac{c}{4d\ n(\nu_1)} \cdot (N_2 - N_1)$$

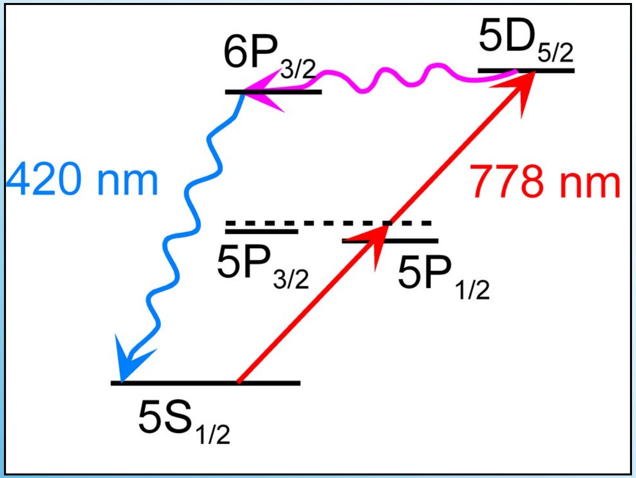


…measuring the beat signal with a frequency meter (accuracy better than 300 kHz)

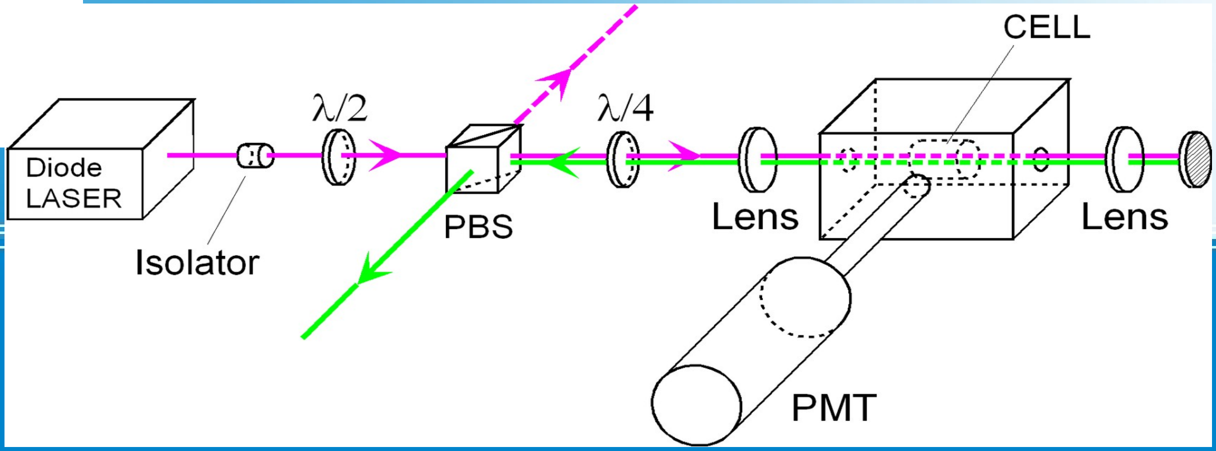
Precision measurements

Secondary frequency standard: Rb 5S – $5D_{5/2}$ 2 photon transition (@ 778 nm) measured with 8 kHz accuracy

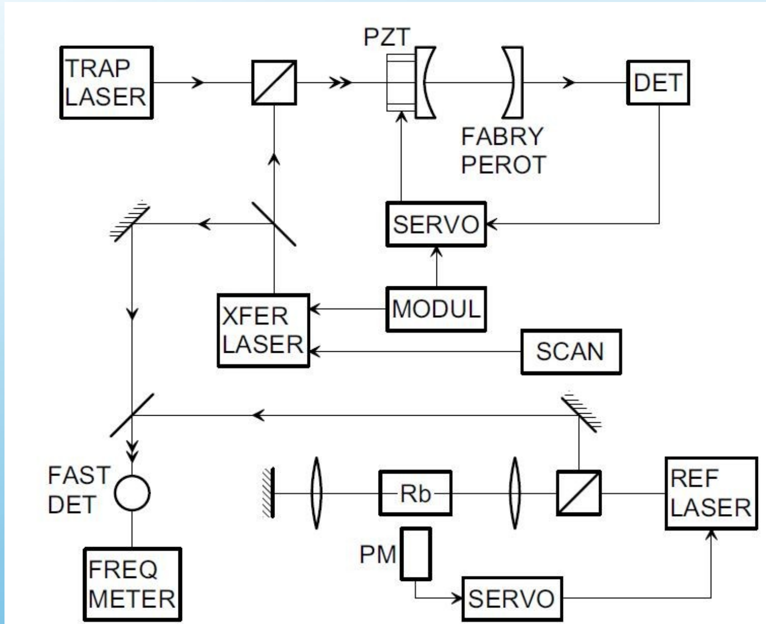


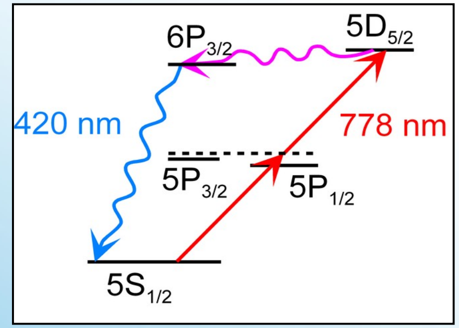


Lock-in detection + stabilization



Precision measurements





Secondary frequency standard:
Rb 5S–5D$_{5/2}$ 2 photon transition @ 778 nm
measured with 8 kHz accuracy

Isotope	209	210	211
Trapping freq. (GHz)	417415.0914(90)	417412.4493(90)	417412.6303(90)
Repumping freq. (GHz)	366897.43(5)	366898.70(5)	366895.57(5)

Accuracy:

Calibration	5 MHz
Fabry-Perot maxima	2 MHz
Refractive index of air	2 MHz
TOTAL	9 MHz

Published in Opt. Lett. 34, 893,2009

LASER SPECTROSCOPY DIFFUSION COEFFICIENT MEASUREMENTS

MOT dynamics

$$\begin{cases} \dot{N}_t = LN_v - CN_t - BN_t^2 - AN_vN_t - \Gamma_r N_t \\ \dot{N}_v = -(L+W)N_v + CN_t + BN_t^2 + AN_vN_t - \Gamma_r N_v + f \end{cases}$$

$$\begin{cases} \dot{N}_t = LN_v - CN_t \\ \dot{N}_v = CN_t - LN_v - WN_v + I \end{cases}$$

$$L = \frac{1}{4\sqrt{\pi}} \frac{v_c{}^4}{\overline{v_T}^3} \frac{3\pi w^2}{4\pi R^3}$$

loading rate

collision rate

$$W \equiv \frac{1}{\tau_{loss}} \equiv \frac{1}{\tau_{esc}} + \frac{1}{\tau_{sto}} + \frac{1}{\tau_{dec}}$$

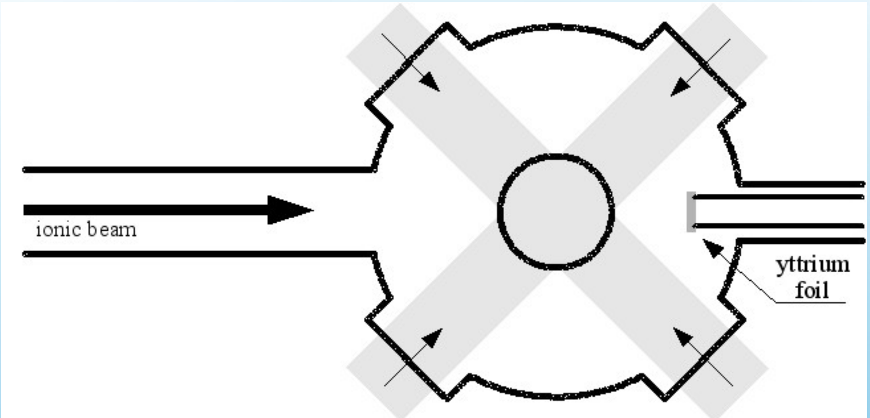
250 ms 1500 ms 275 s

Loss rate

$$N_t = \frac{LI}{CW} \quad N_v = N_{eq} = \frac{I}{W}$$

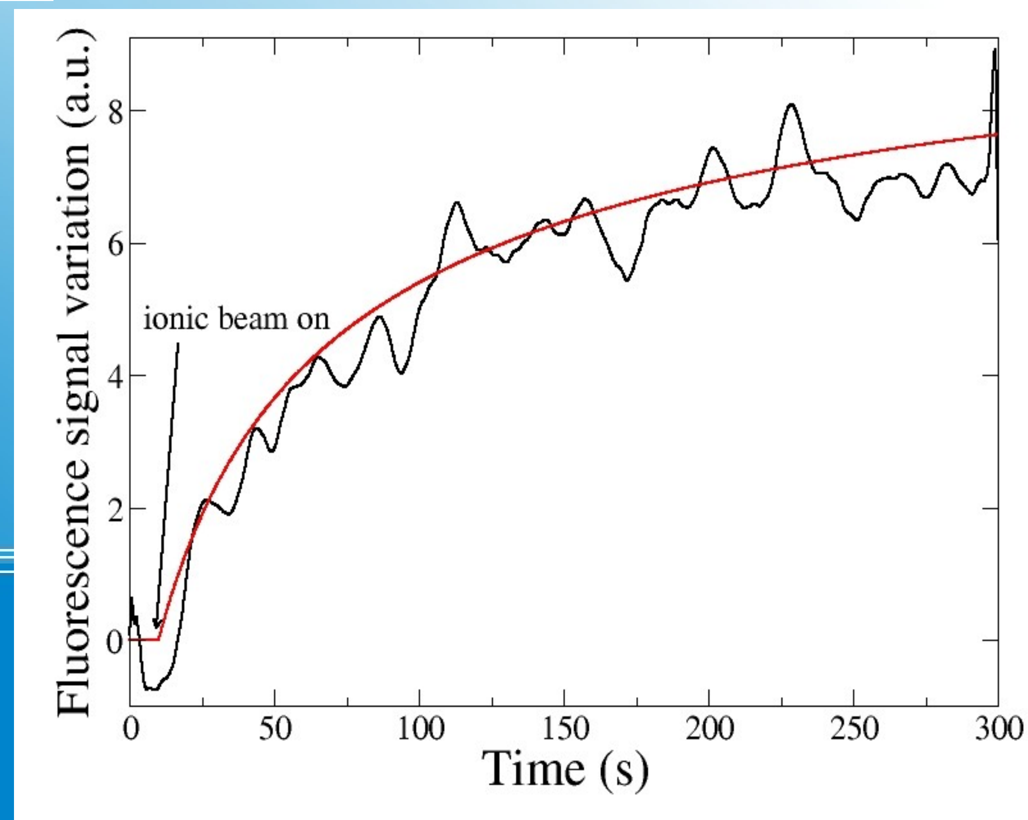
$$N_t = \frac{3}{8\sqrt{\pi}} \left(\frac{v_c}{v_{th}}\right)^4 \frac{R_b^2 l I}{C r^3} \frac{1}{1 + \frac{6lR^2}{\chi r^3}}$$

Tests on neutraliser



from calculated implantation depth of 51 Å diffusion coefficient of Fr is determined for the first time

$$\frac{\partial N(x,t)}{\partial t} = D\frac{\partial^2 N(x,t)}{\partial x^2} - \Gamma_r N(x,t) + \varphi(x,t)$$

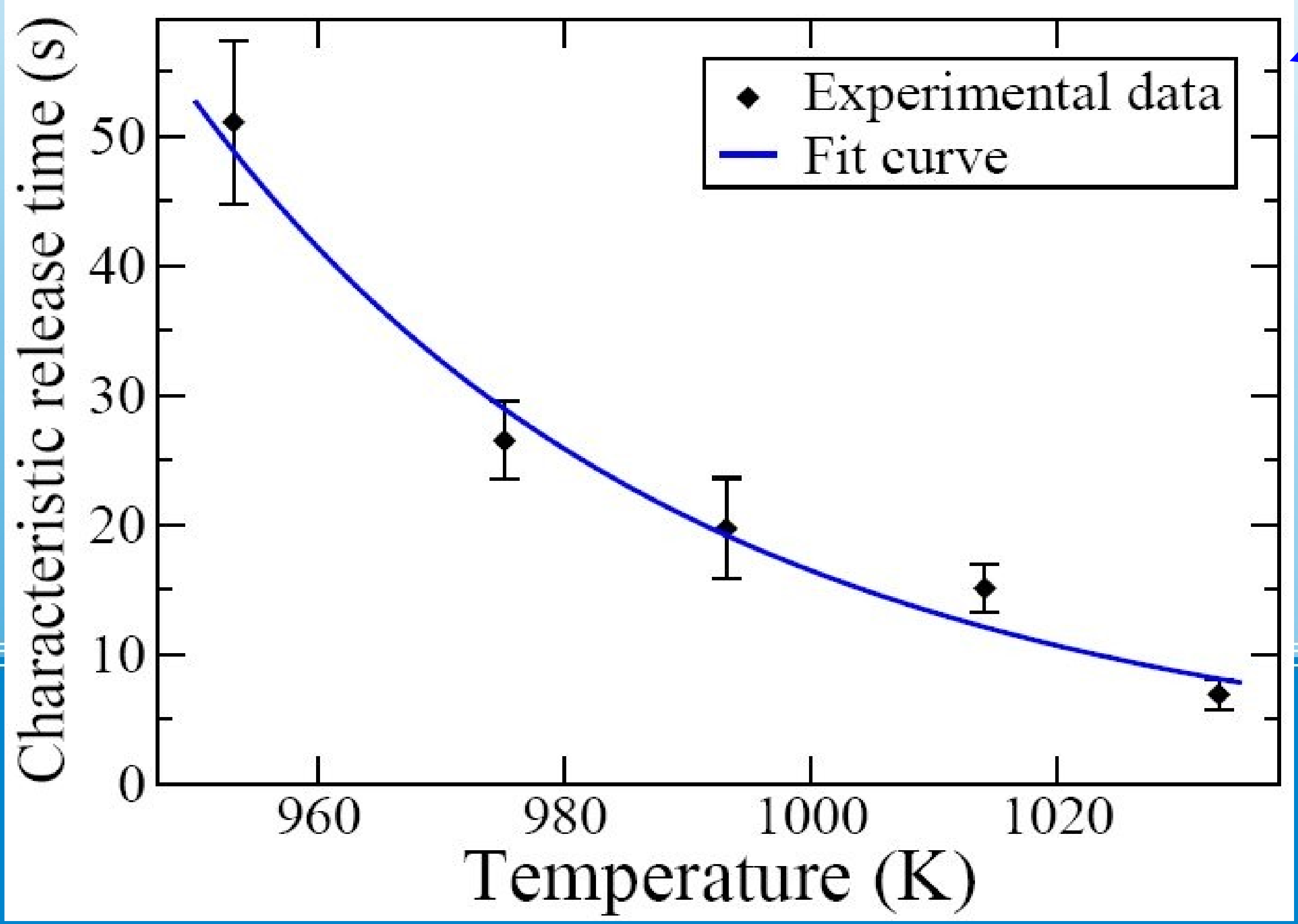


Diffusion time measurements

fit function comes from diffusion equation in the neutraliser

parameters of fit

τ_d , $A \propto N_0$



from calculated implantation depth of 51 Å diffusion coefficient of Fr is determined for the first time

Published in Phys.Rev.A **78**, 063415 2008

Diffusion time measurements

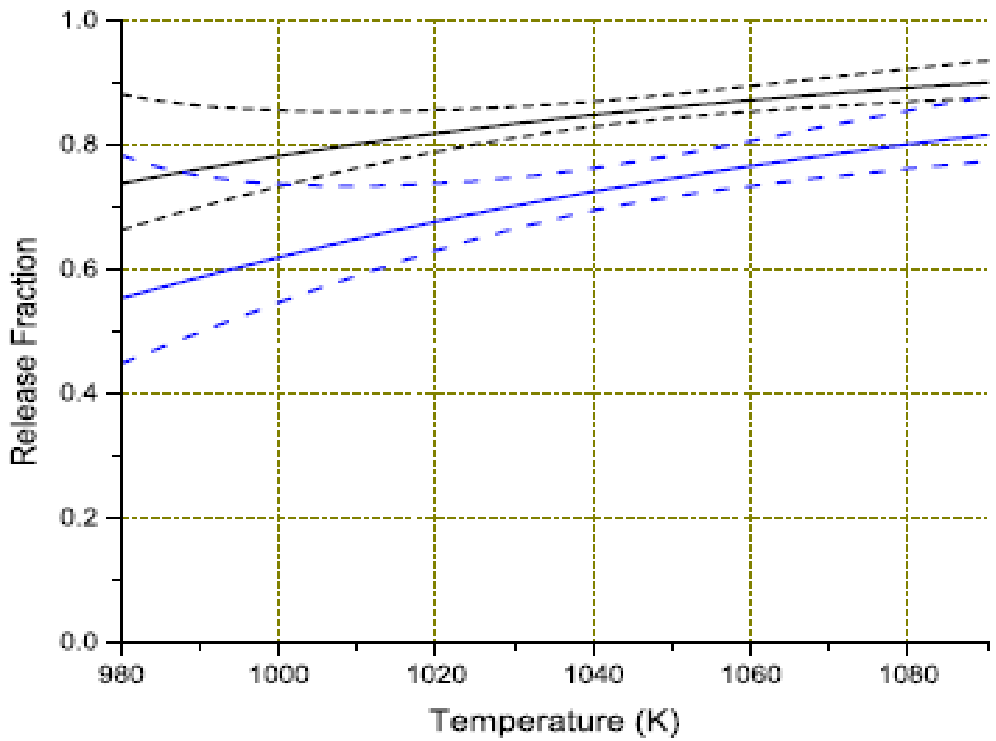
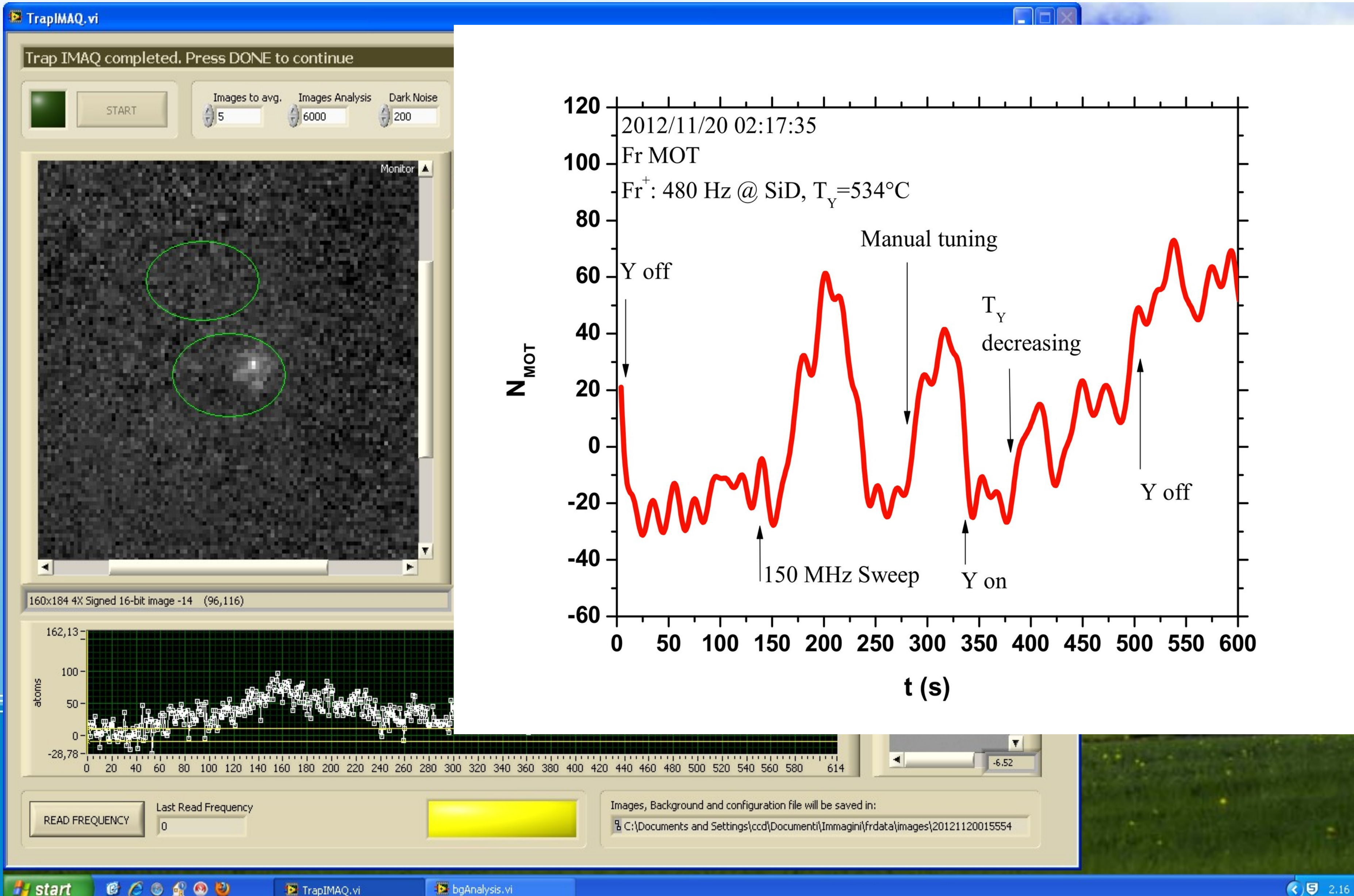


FIG. 8. (Color online) Calculated release fraction vs temperature for isotope 210 (black curve) and 209 (blue curve), according to the Arrhenius law and E_a and τ_{1000} given from our fit. Dashed curves give the uncertainty interval.

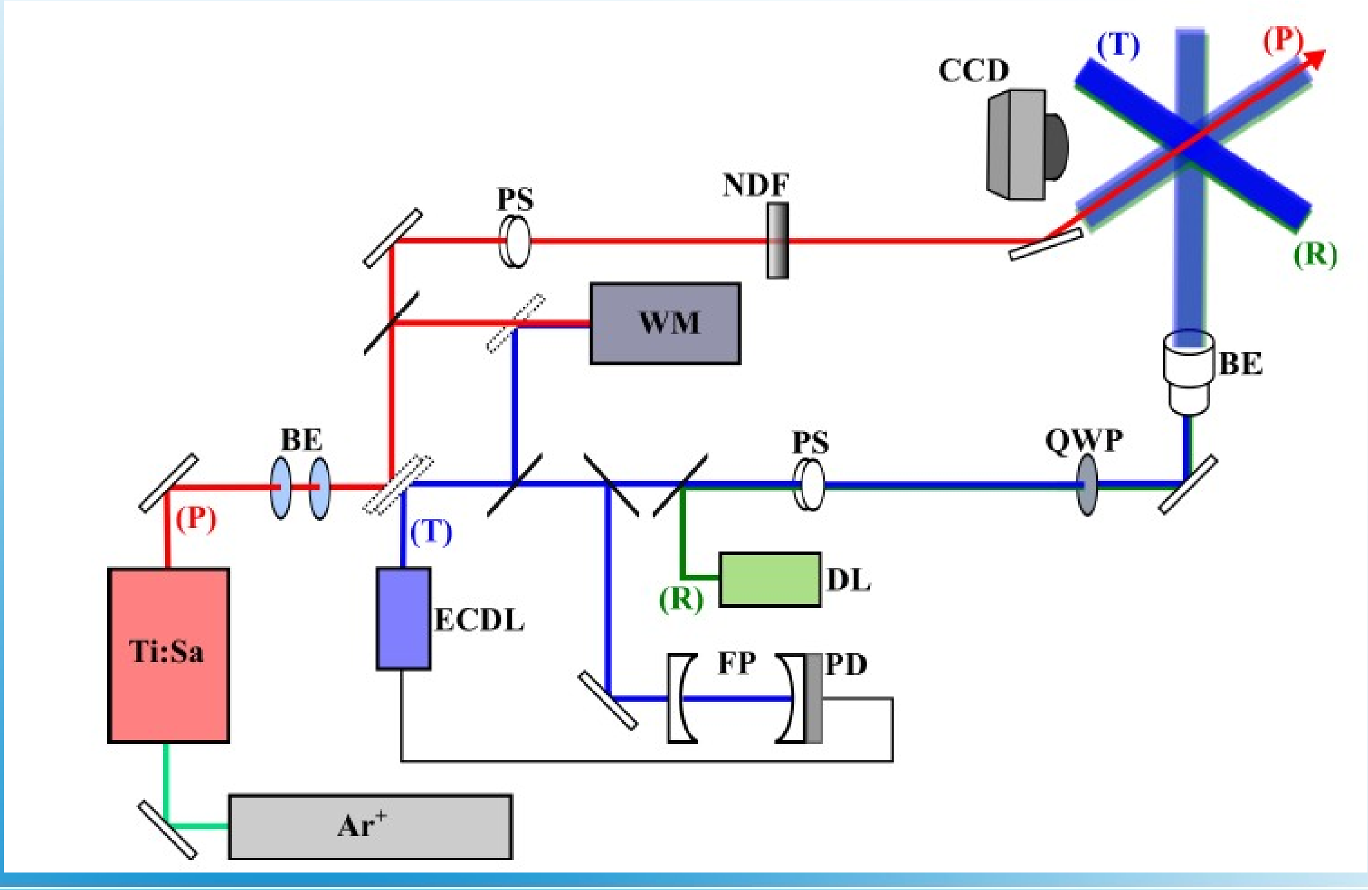
Neutralizer behaves pretty well!

Room temperature neutralizer trap!

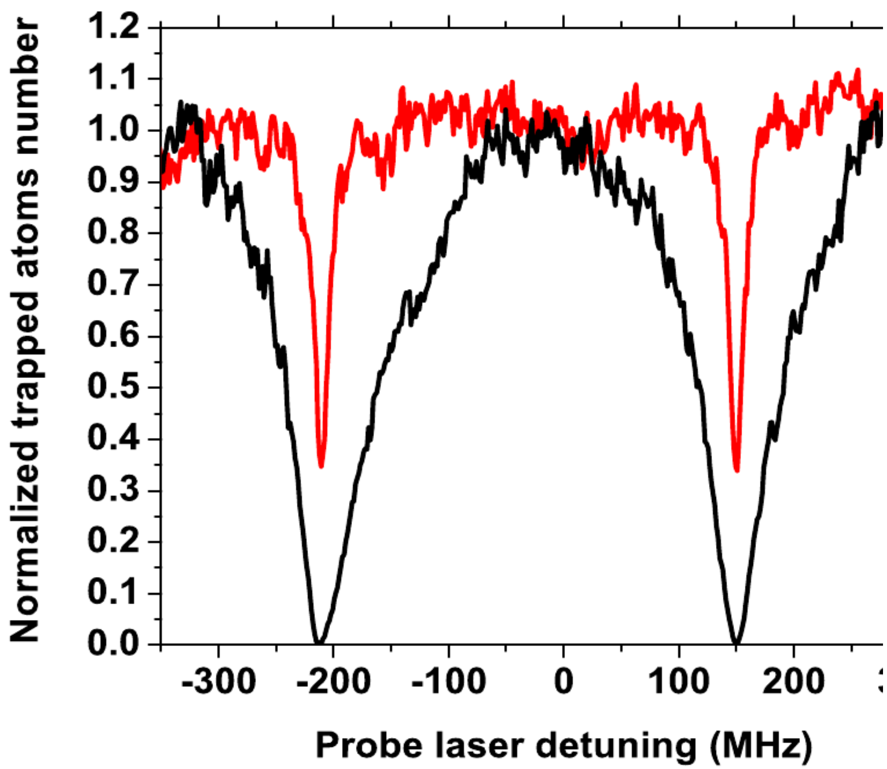


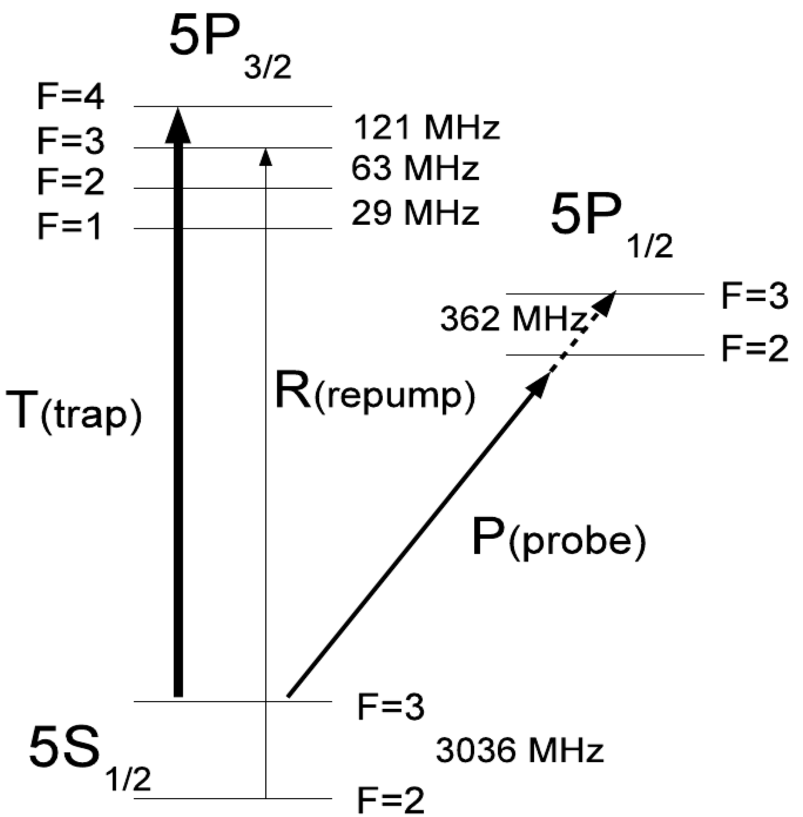
DETECTION OF LINES BY CHANGE IN TRAPPED ATOM NUMBERS

Detection setup (Rb or Fr)

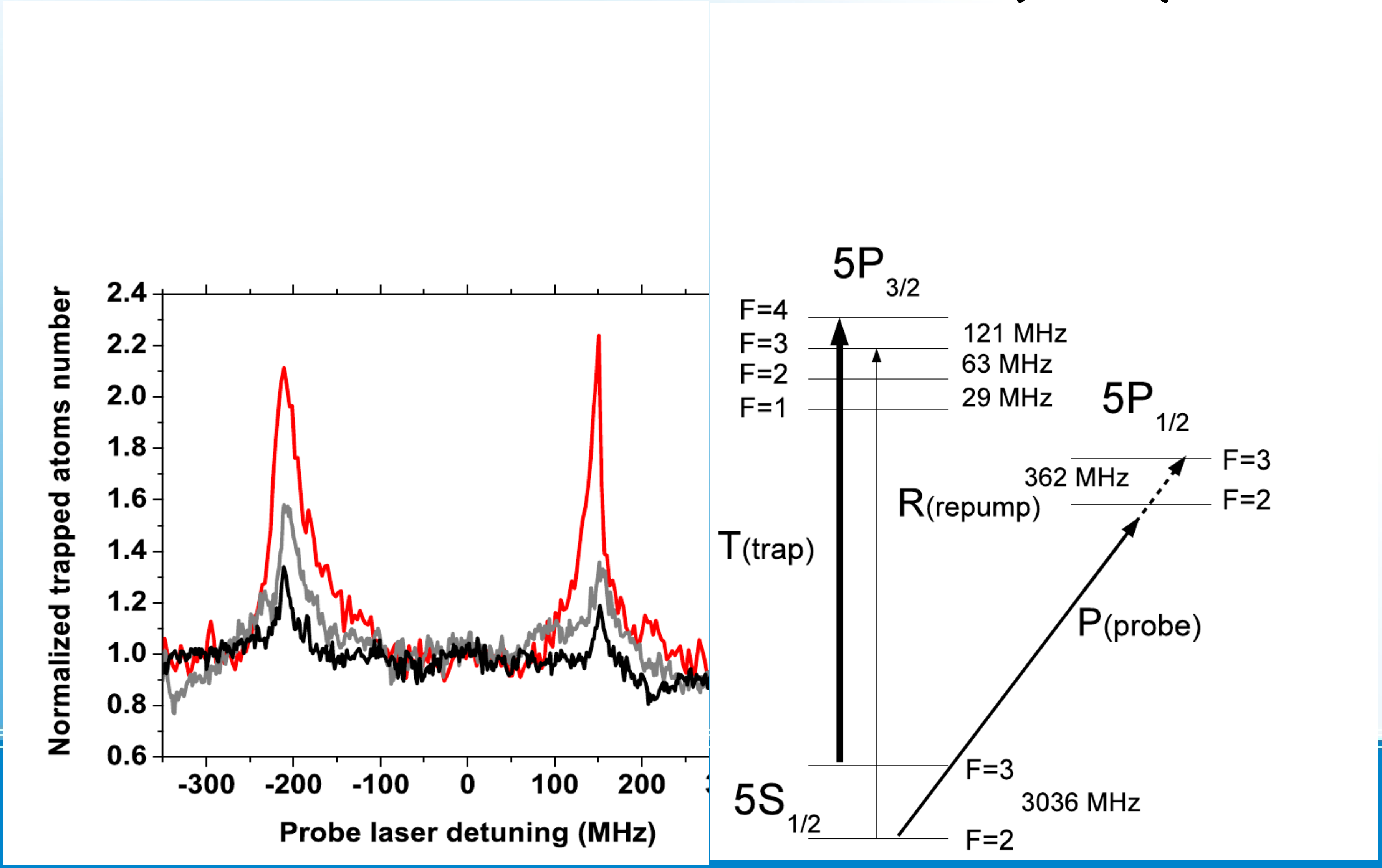


Detection results (Rb)

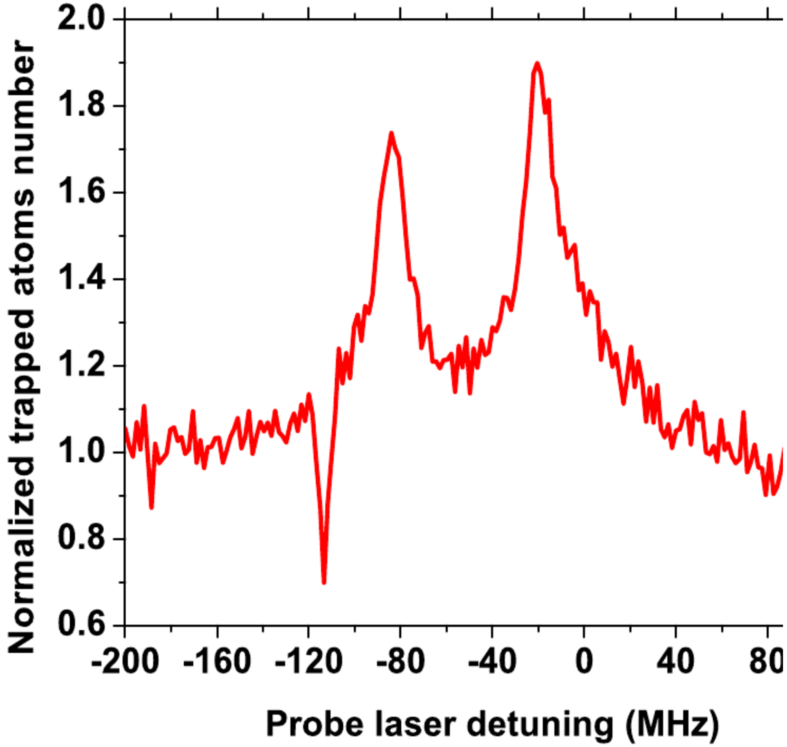


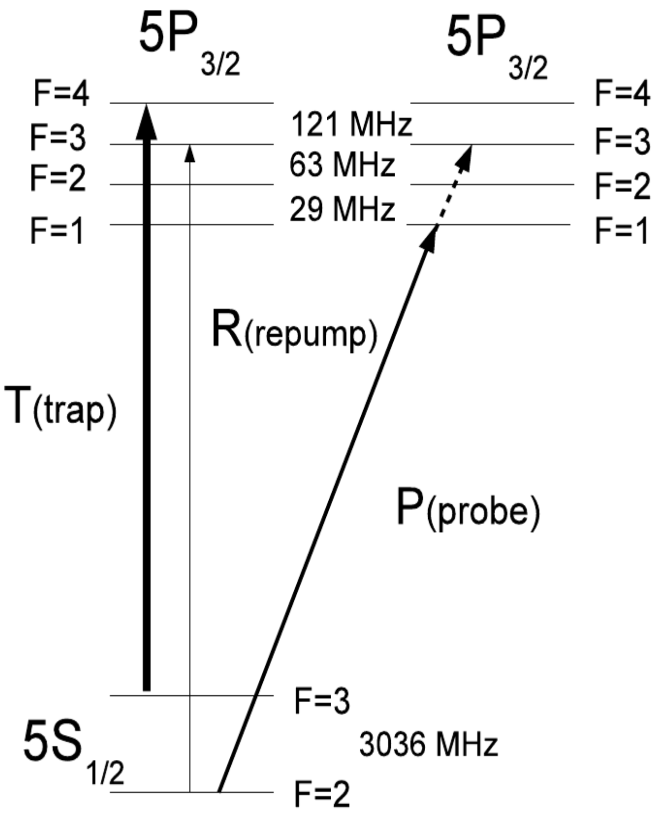


Detection results (Rb)

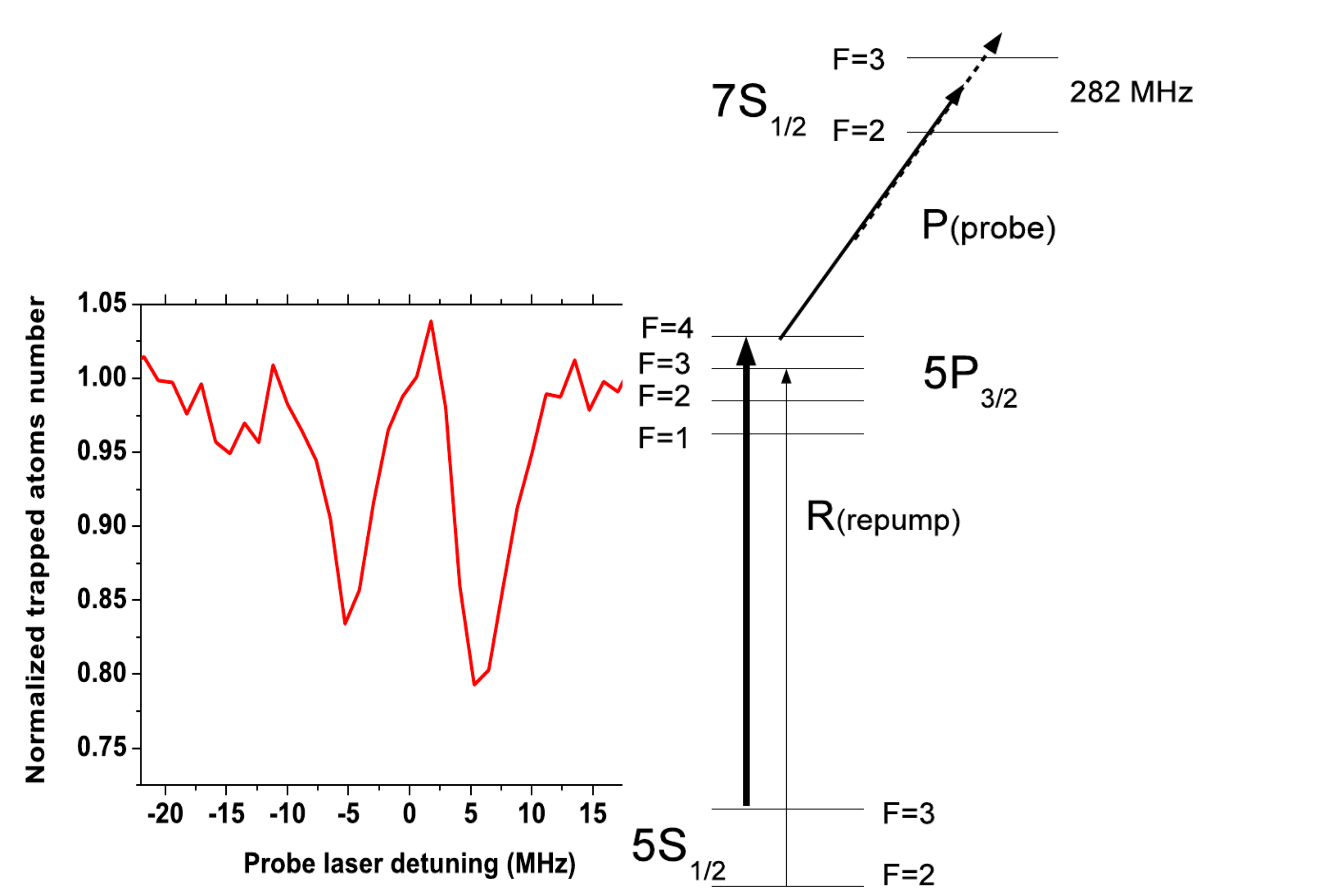


Detection results (Rb)

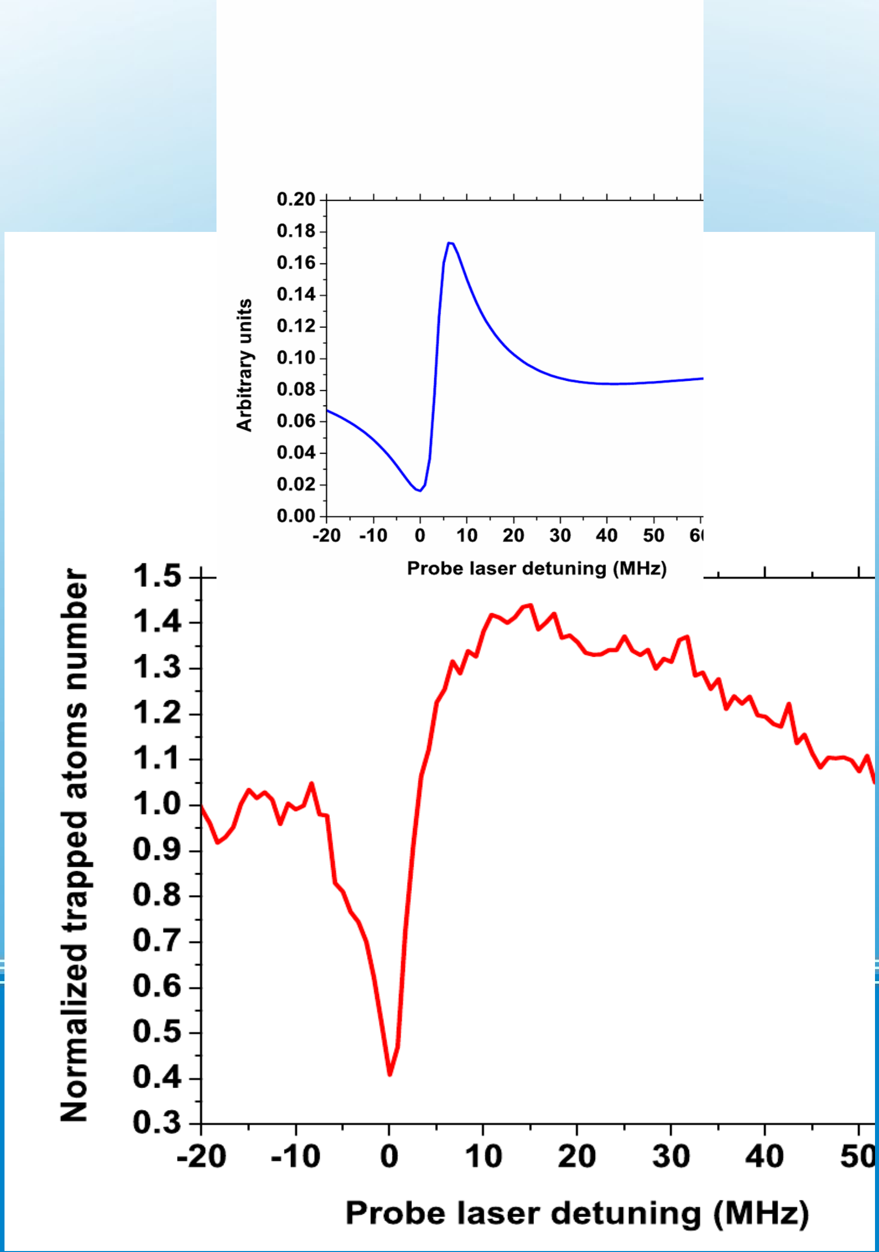


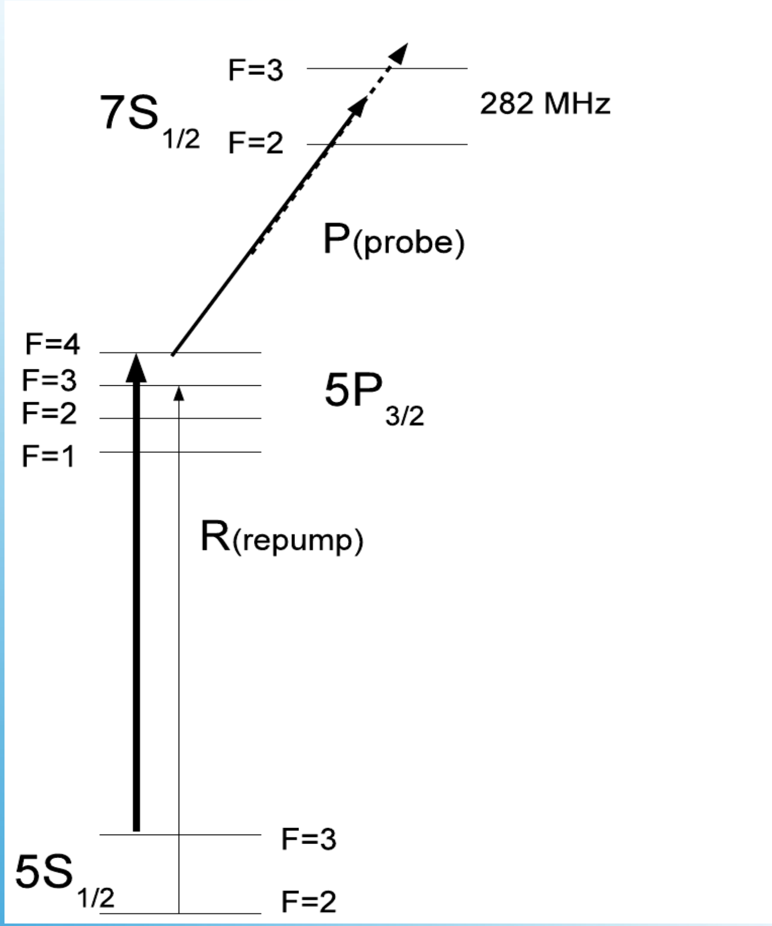


Detection results (Rb)

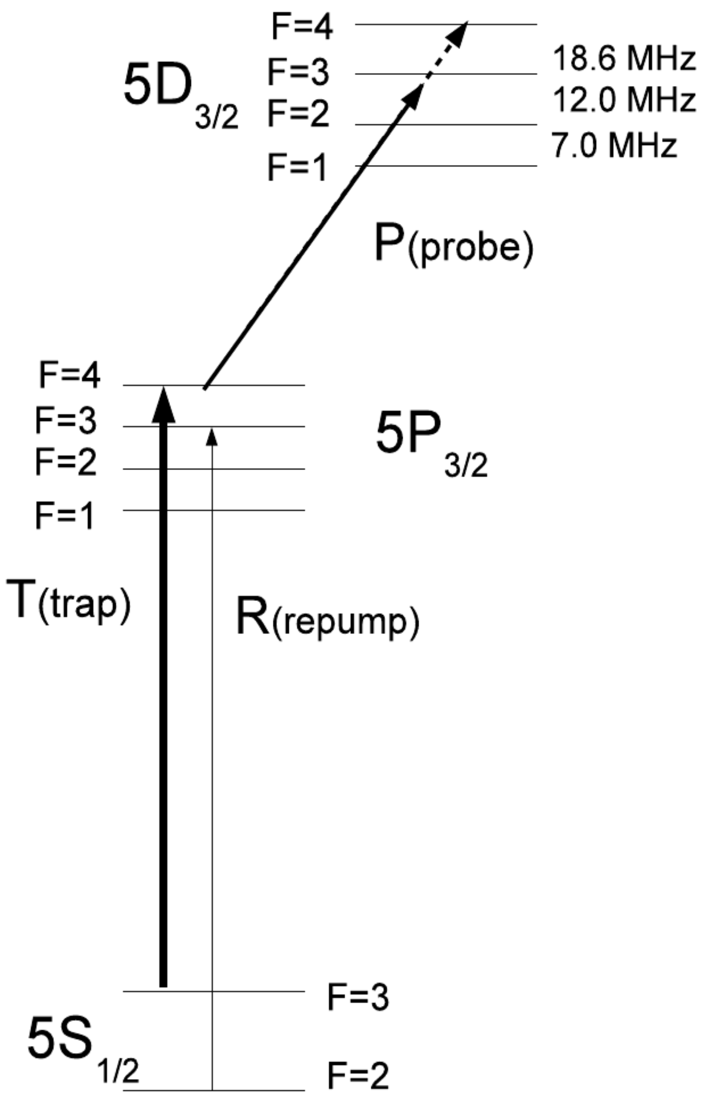


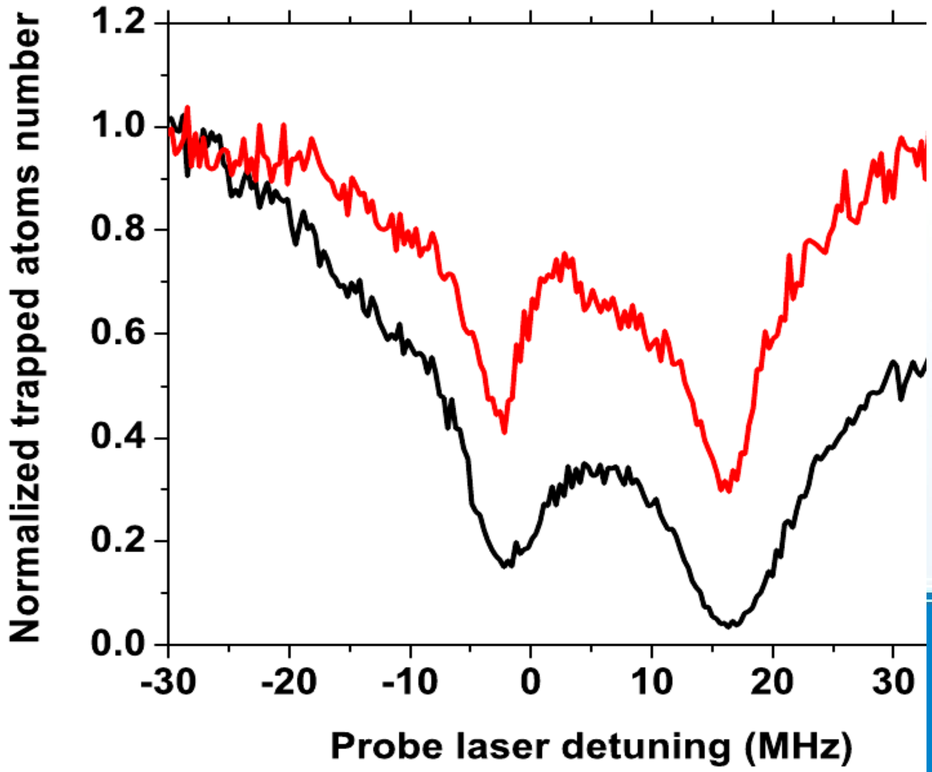
Detection results (Rb)



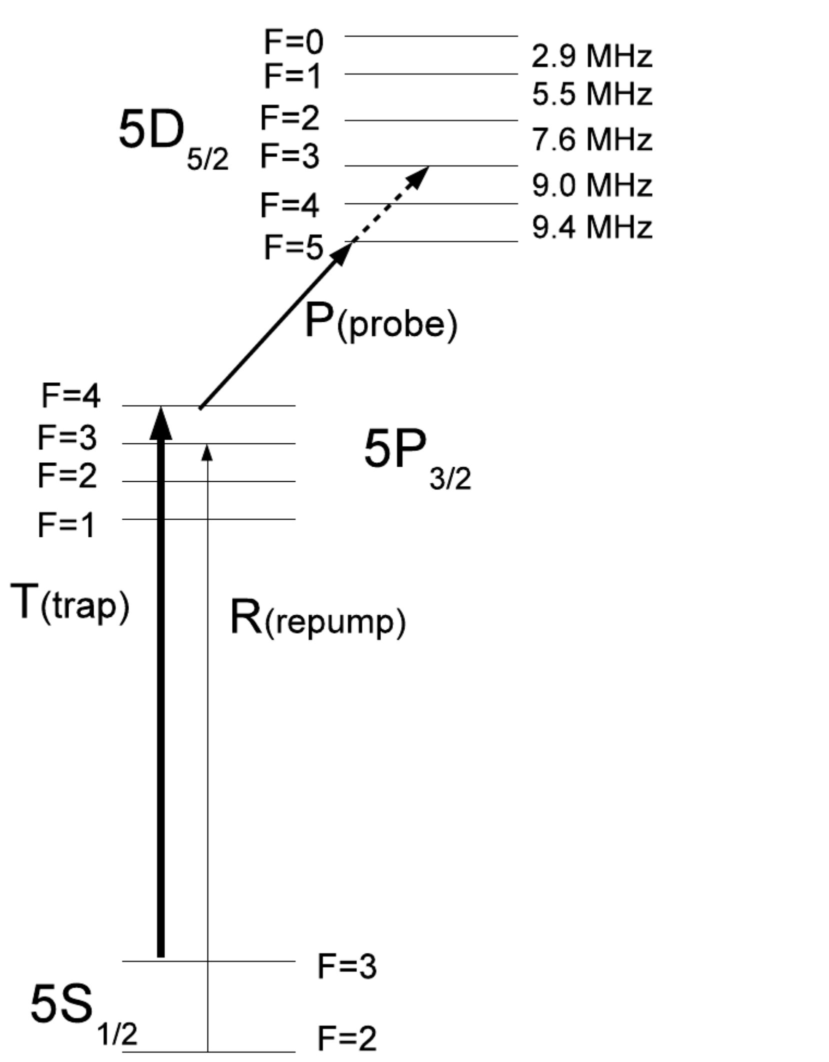


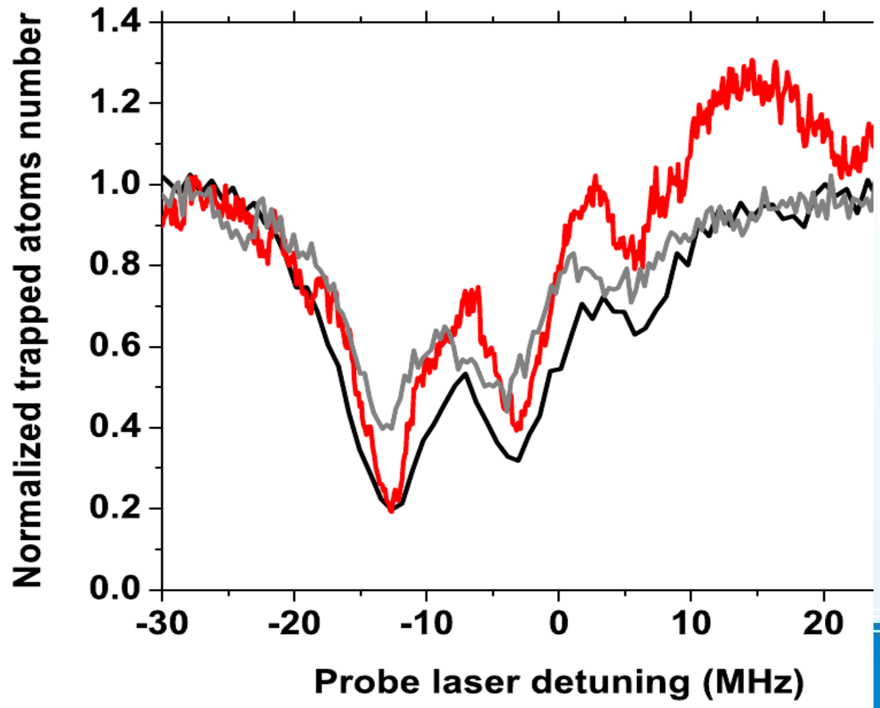
Detection results (Rb)





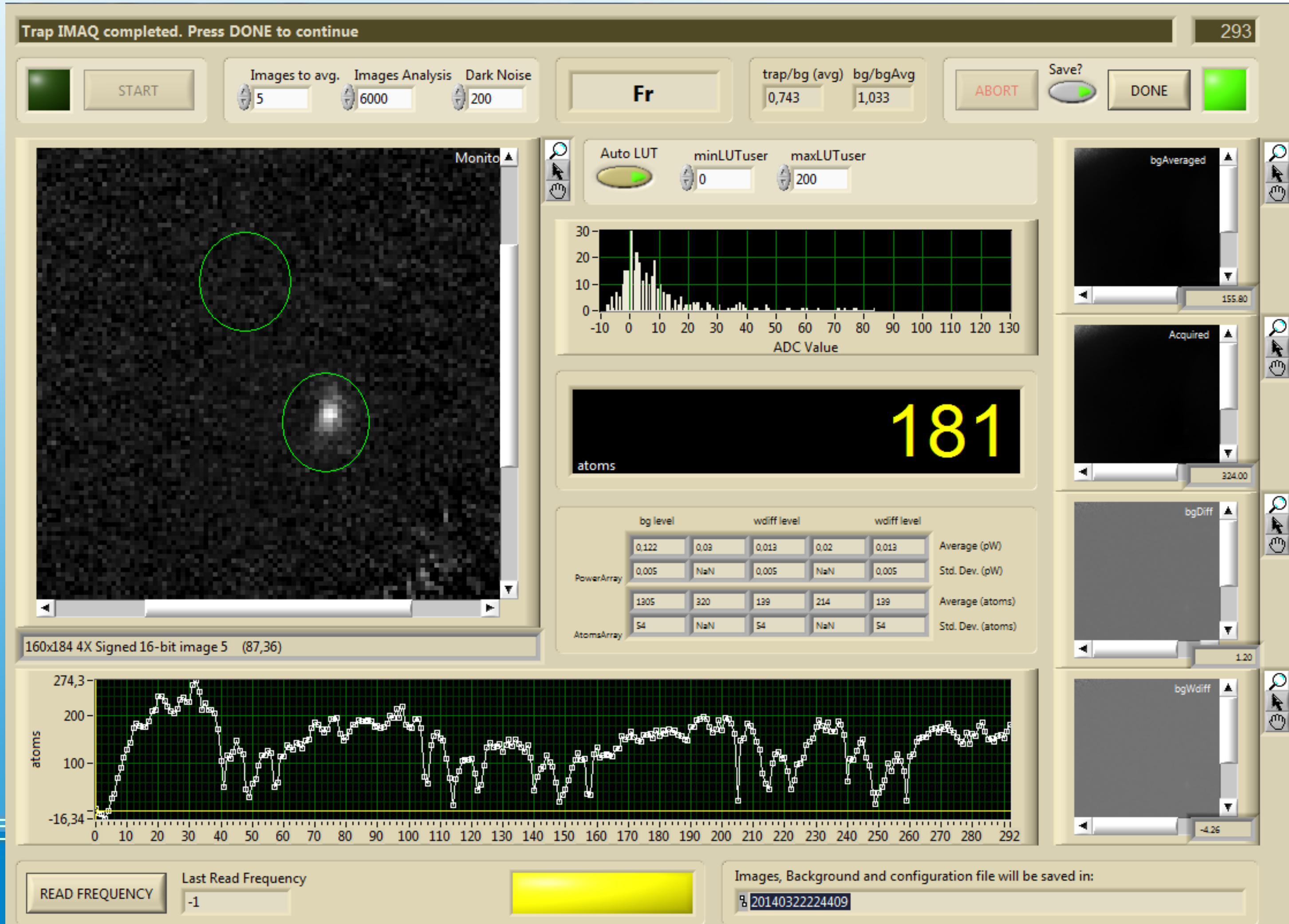
Detection results (Rb)





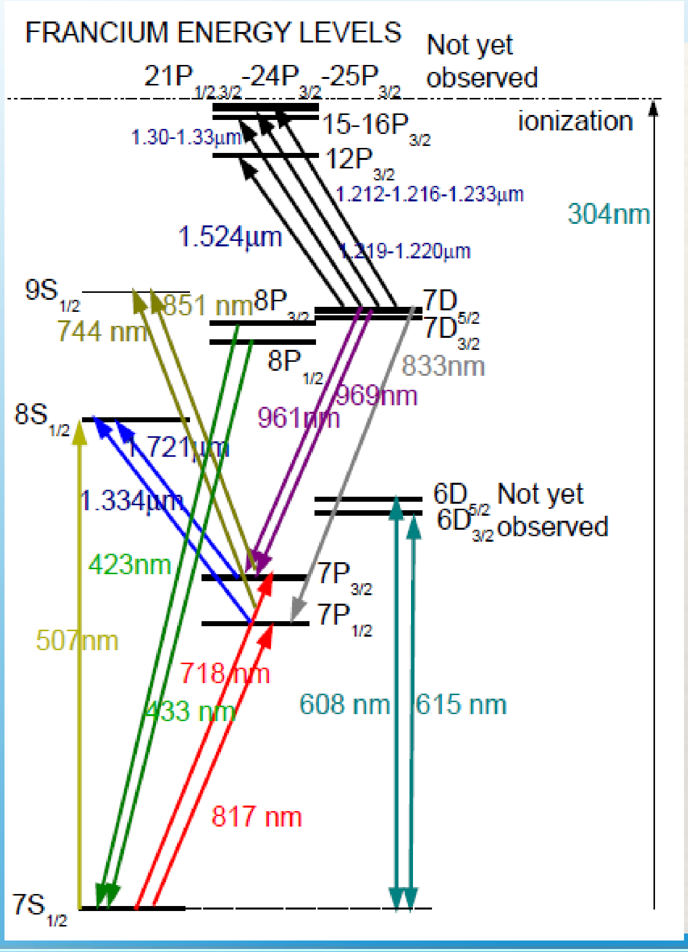
Published in Meas. Sci. Technol. **24**, 015201 2013
Measurement Science and Technology's Outstanding Paper awards for 2013
http://iopscience.iop.org/0957-0233/25/7/070201

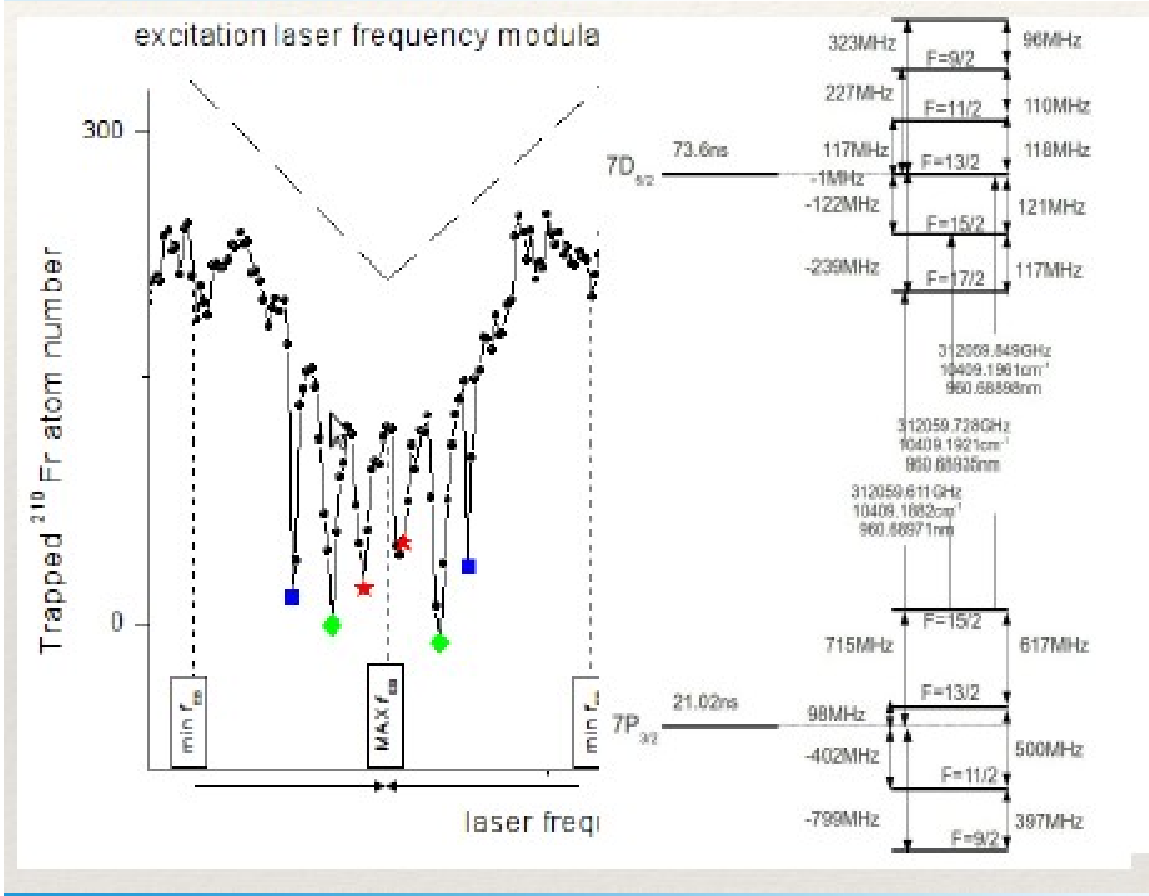
Detection results (Fr – isotope 210)



OPTICS LETTERS

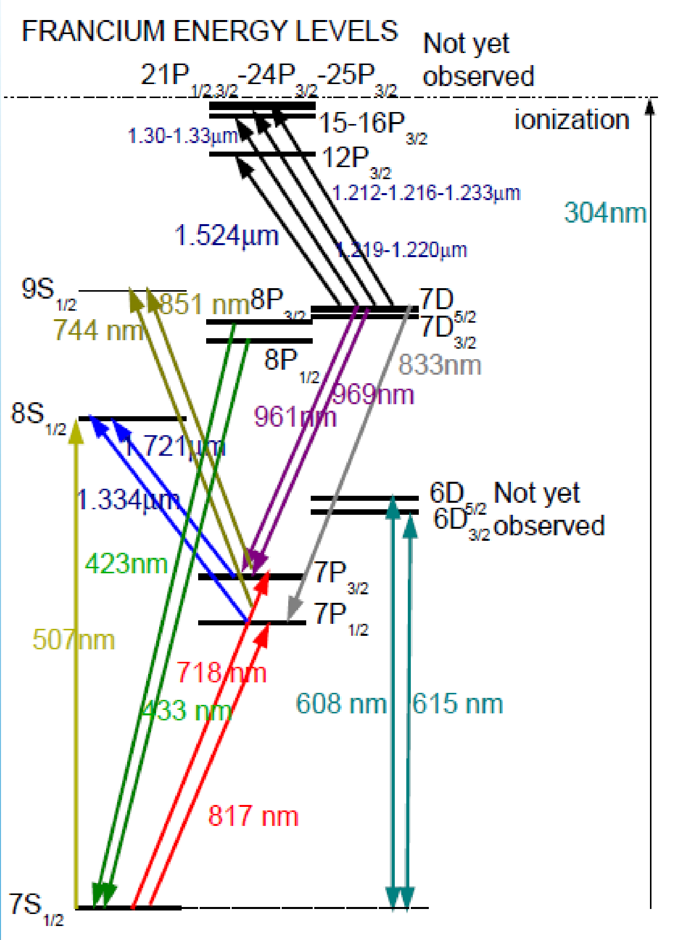
Detection results (Fr – isotope 210)

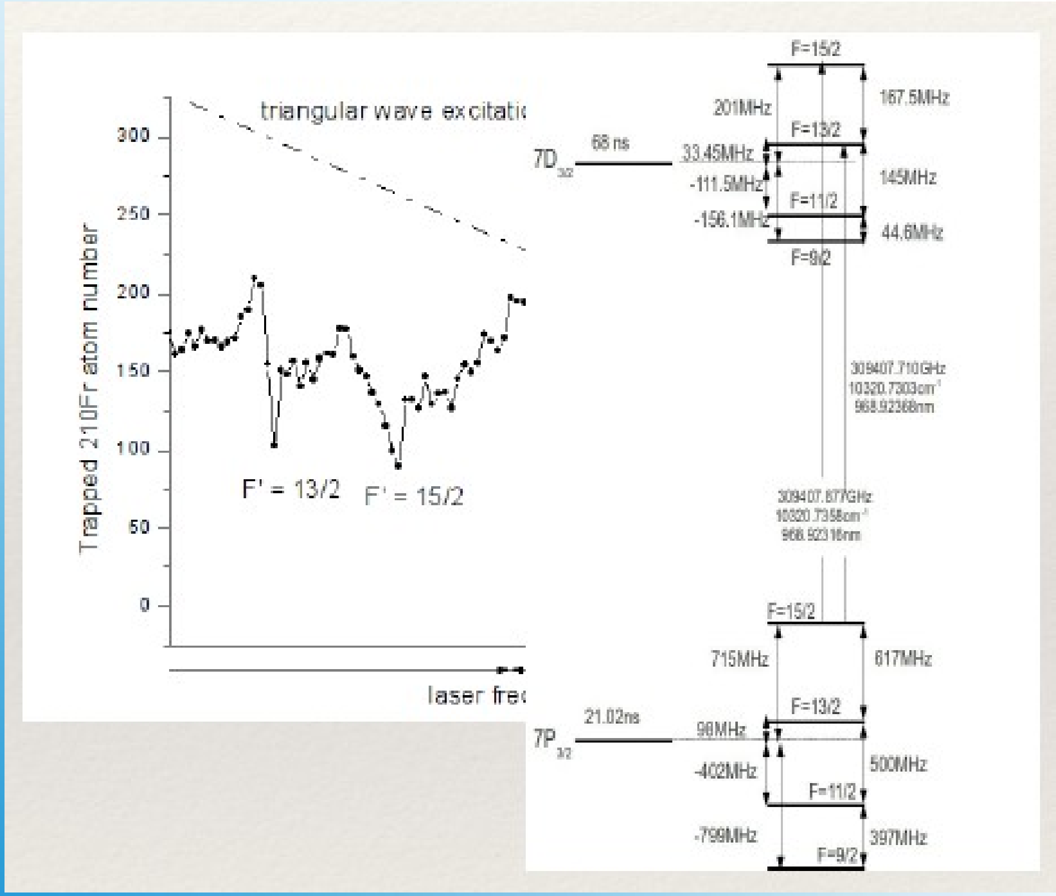




OPTICS LETTERS

Detection results (Fr – isotope 210)

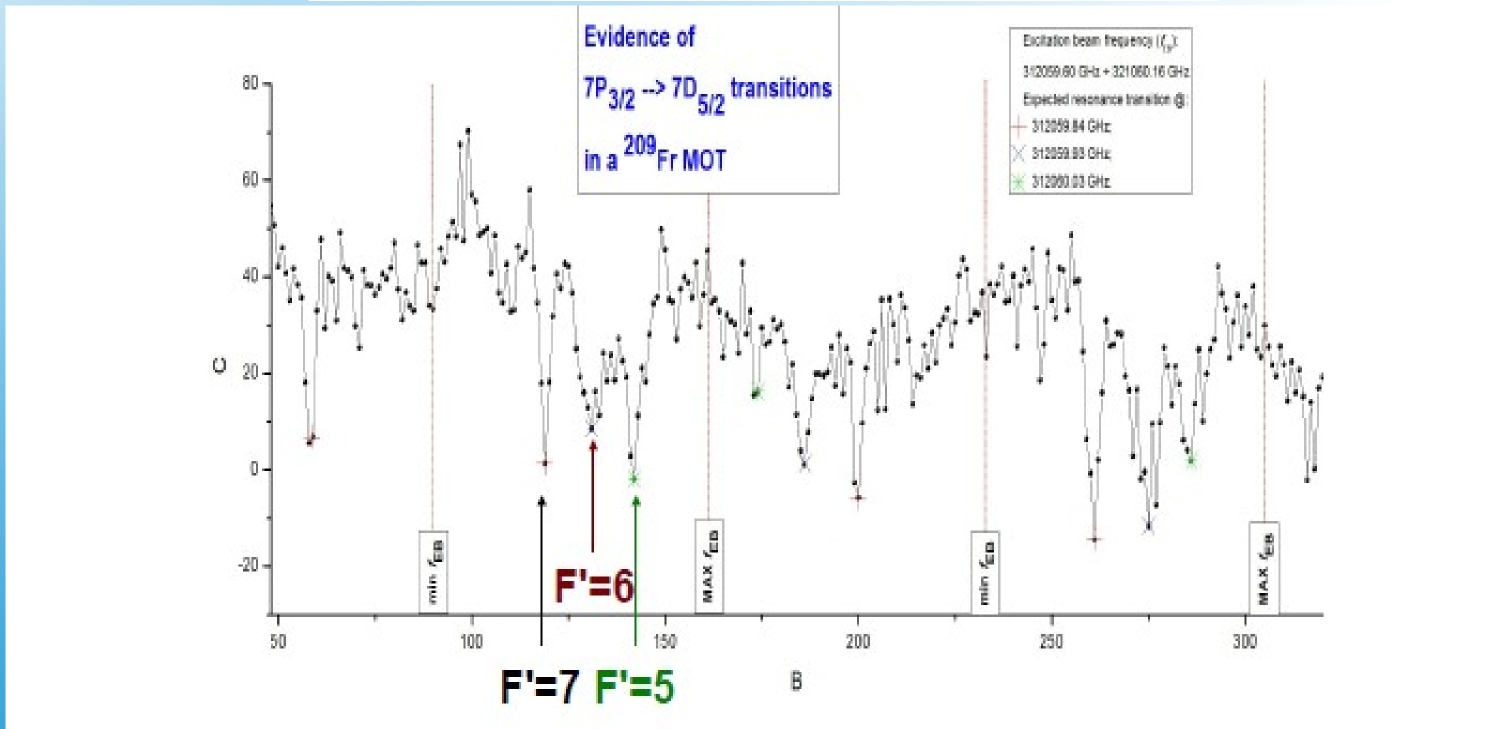




Optics Letters

Detection results (Fr – isotope 209)

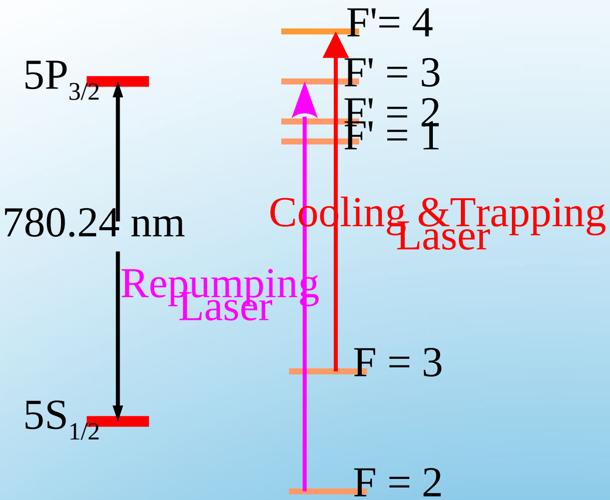
$$H_{\mathrm{hfs}} = A_{\mathrm{hfs}}\mathbf{I}\cdot\mathbf{J} + B_{\mathrm{hfs}}\frac{3(\mathbf{I}\cdot\mathbf{J})^2 + \frac{3}{2}(\mathbf{I}\cdot\mathbf{J}) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}$$
$$+ C_{\mathrm{hfs}}\frac{10(\mathbf{I}\cdot\mathbf{J})^3 + 20(\mathbf{I}\cdot\mathbf{J})^2 + 2(\mathbf{I}\cdot\mathbf{J})[I(I+1) + J(J+1) + 3] - 3I(I+1)J(J+1) - 5I(I+1)J(J+1)}{I(I-1)(2I-1)J(J-1)(2J-1)},$$



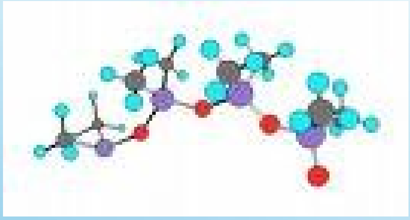
Submitted to Optics Letters

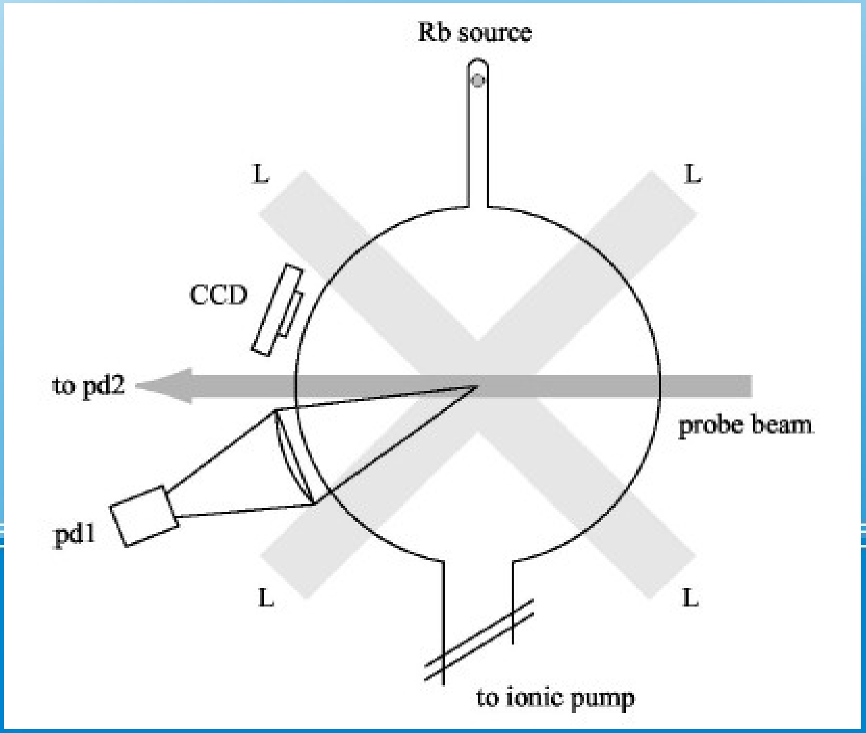
Application: LIAD for MOTs

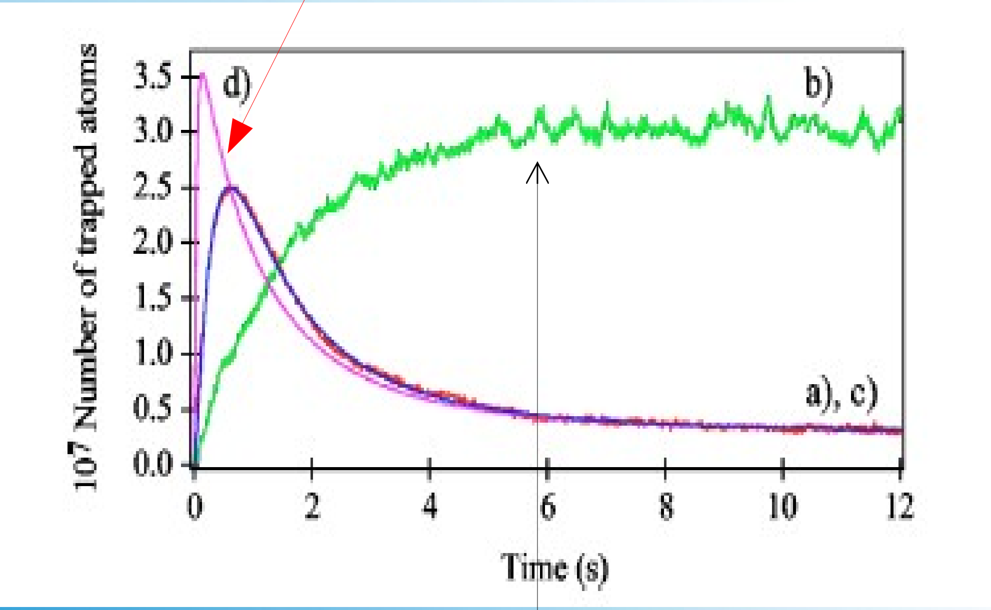
LIAD for MOTs



LIAD MOT loading



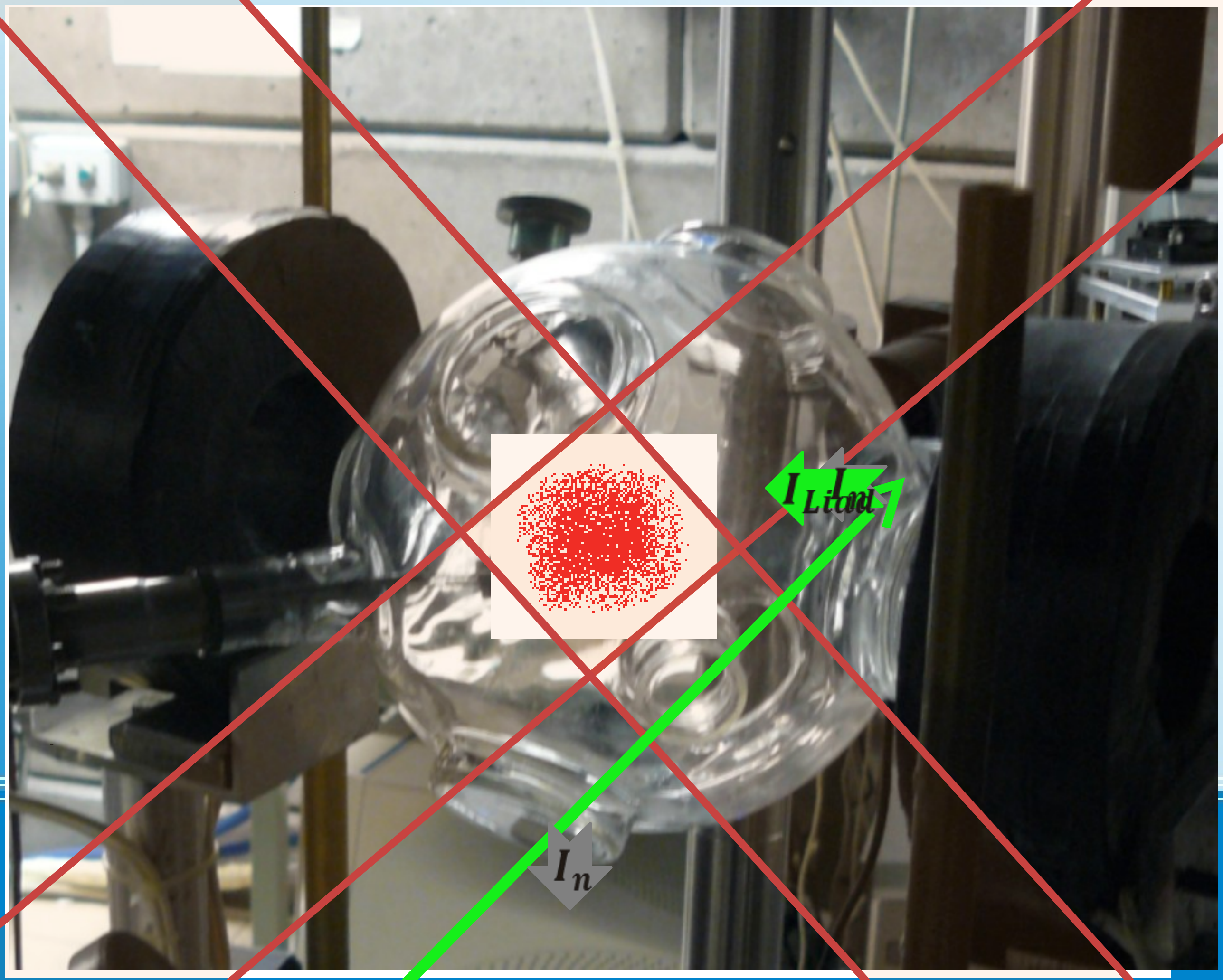




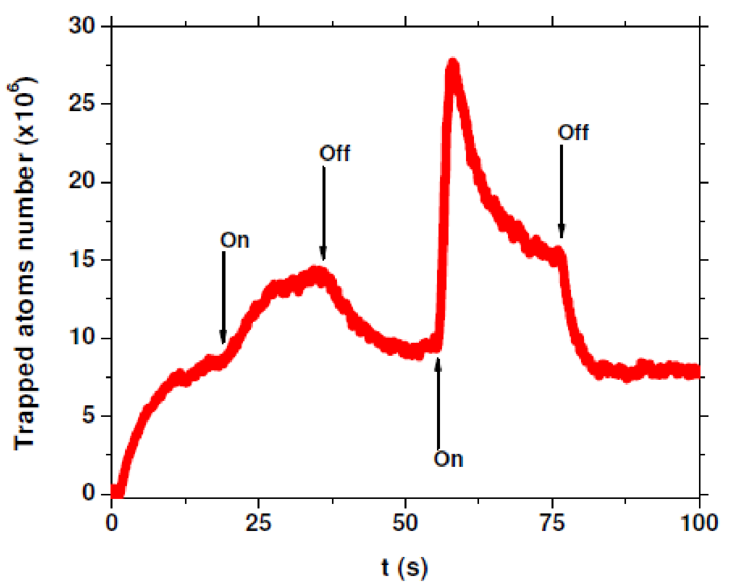
"Usual" MOT loading

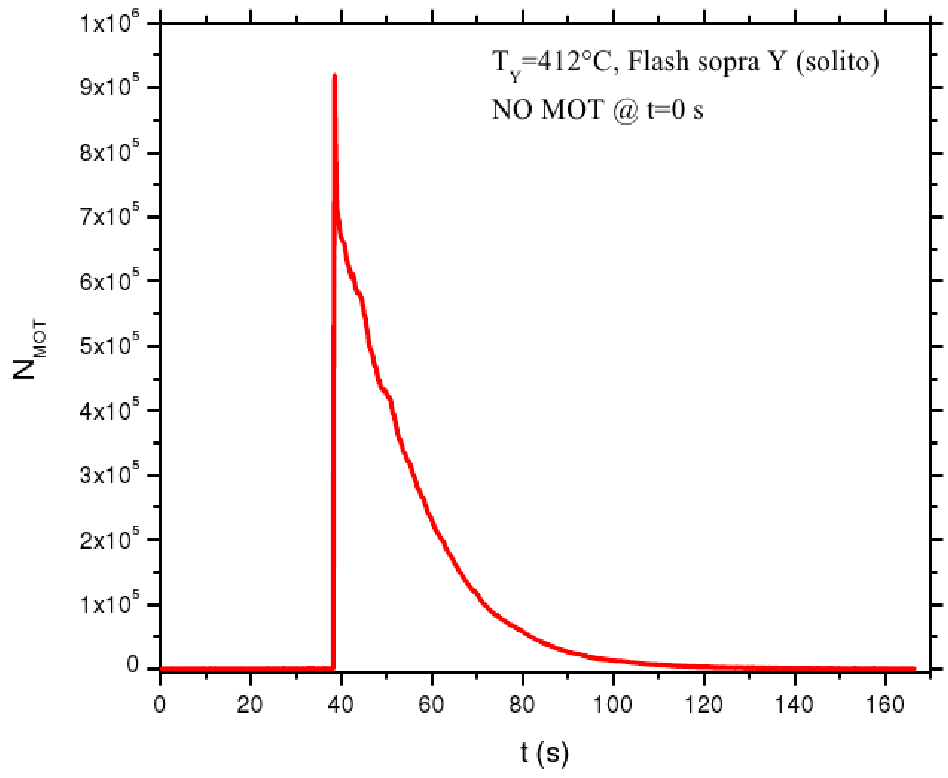
S.N.Atutov et al. Phys.Rev. A 67, 053401 (2003)

LIAD in LNL



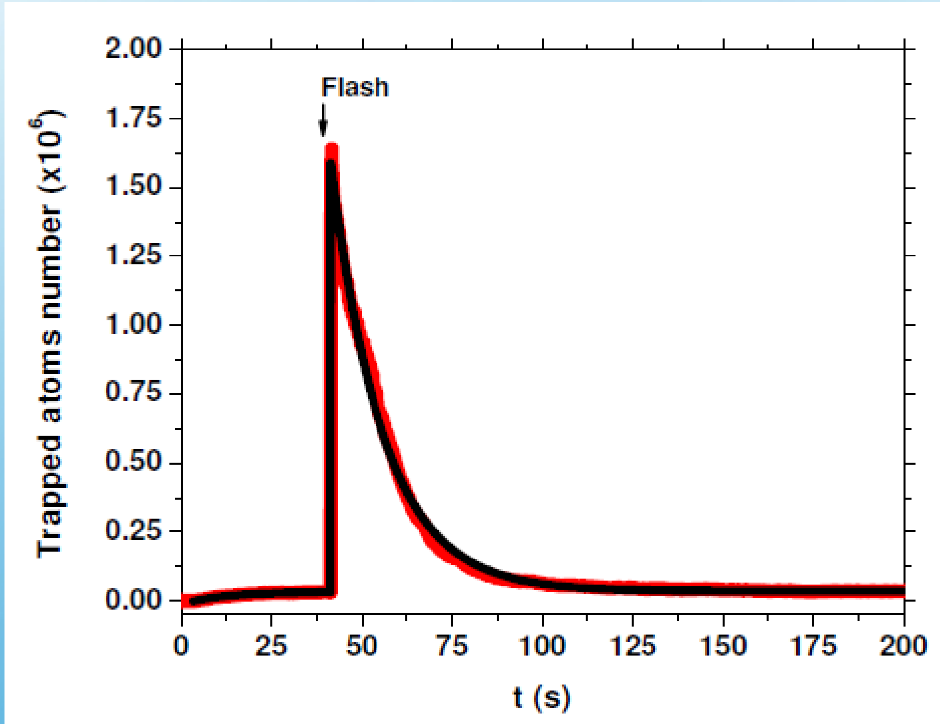
Rb MOT loading from Yttrium!

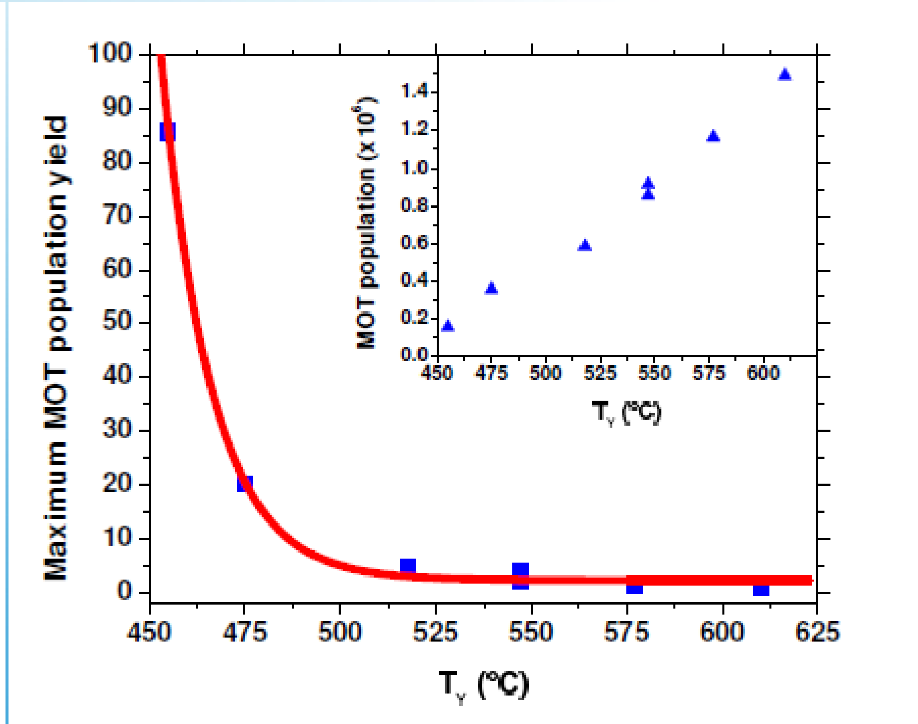




No MOT at the beginning
Very long restoring time – signature of a good coating

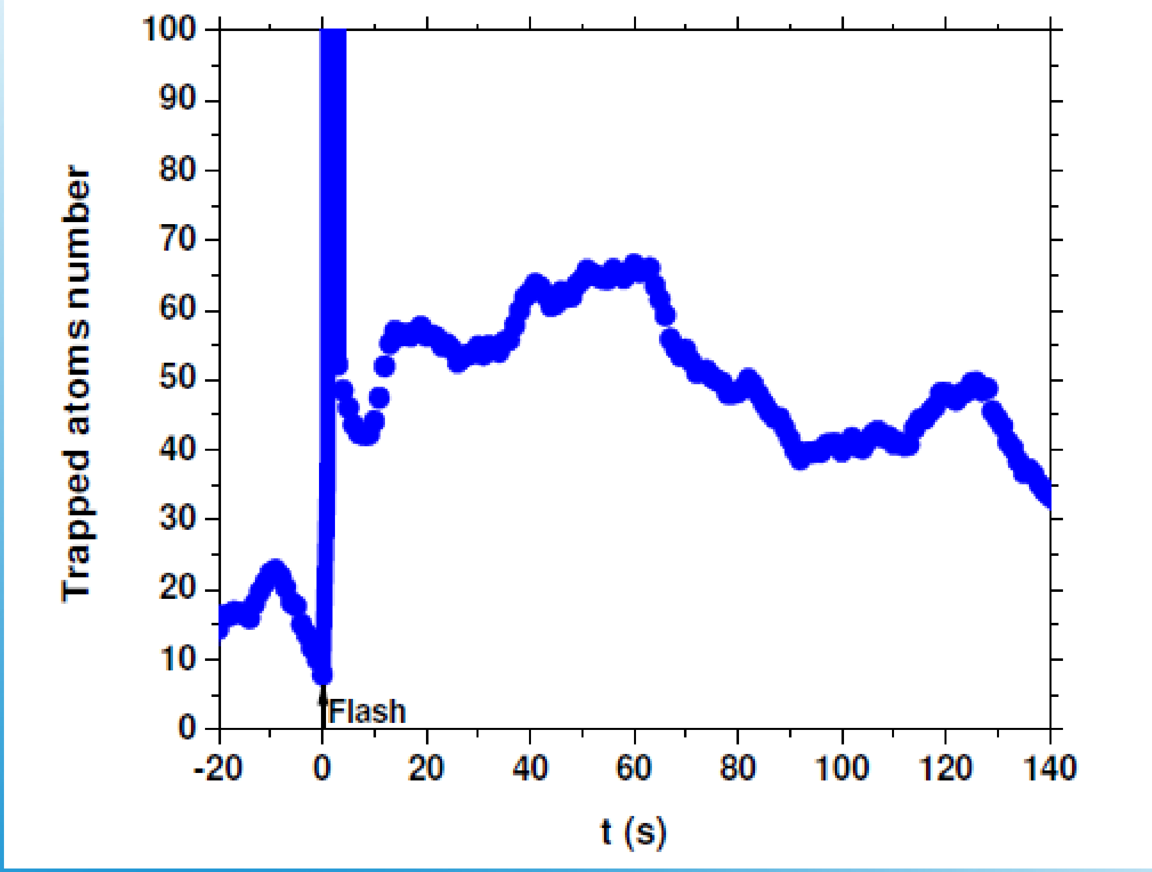
Rb MOT loading from Yttrium



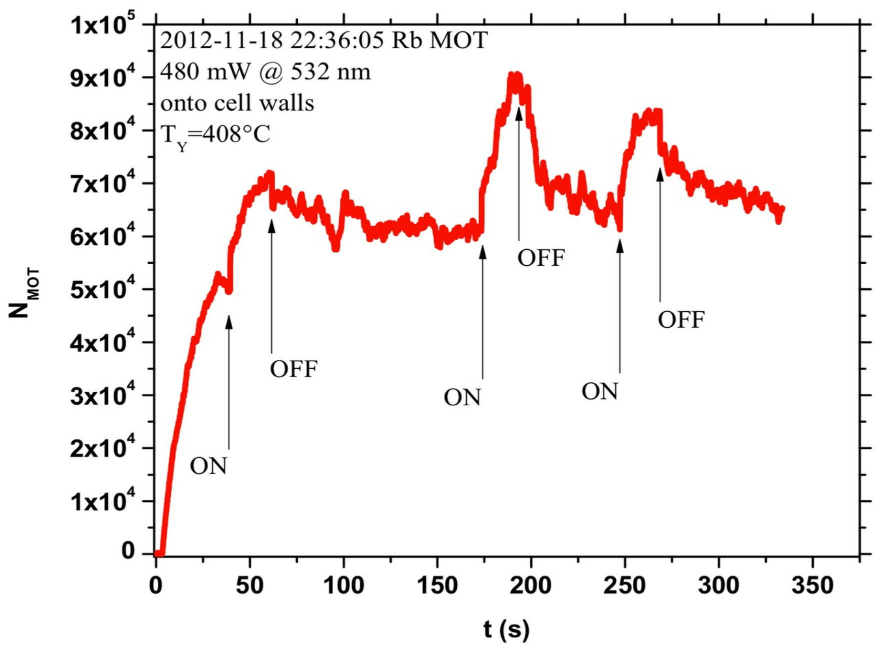


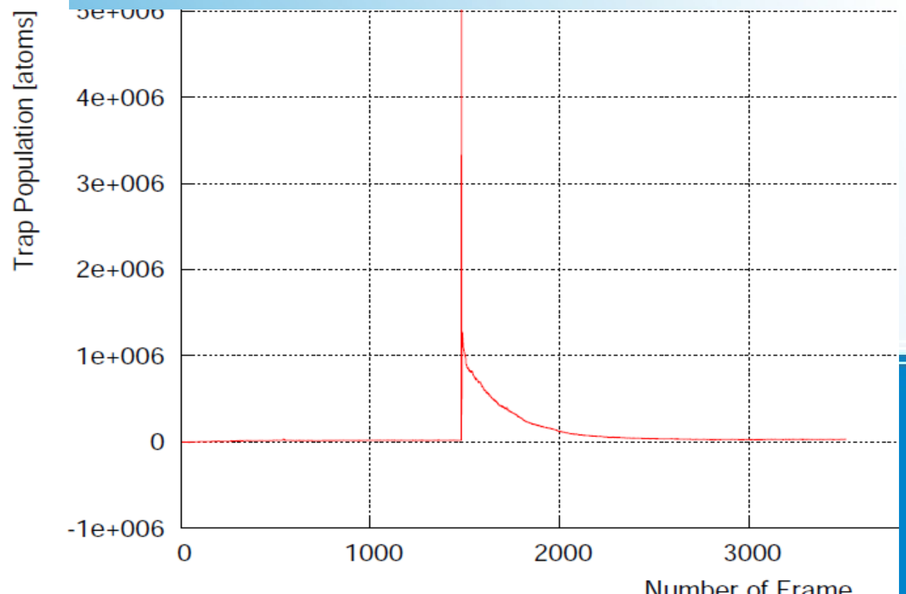
$$N_{trap}(t) = \frac{LI_n}{CW} + A_1 \exp(\gamma_+ t) + A_2 \exp(\gamma_- t) + \frac{LI_{LIAD}}{\gamma_+ - \gamma_-}(\exp(\gamma_+(t-t_0)) - \exp(\gamma_-(t-t_0)))\Theta(t-t_0)$$

Fr LIAD MOT loading from Yttrium

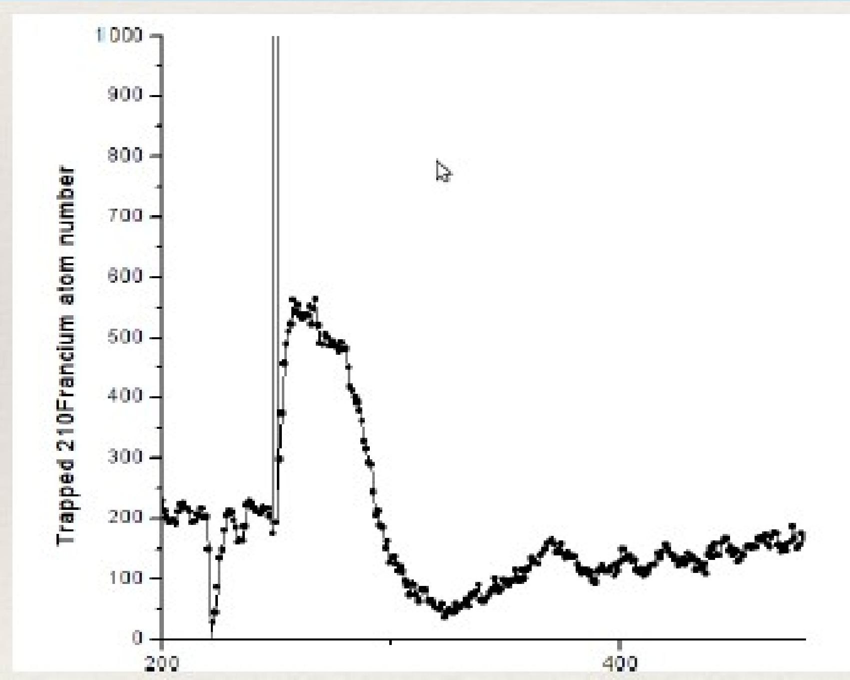


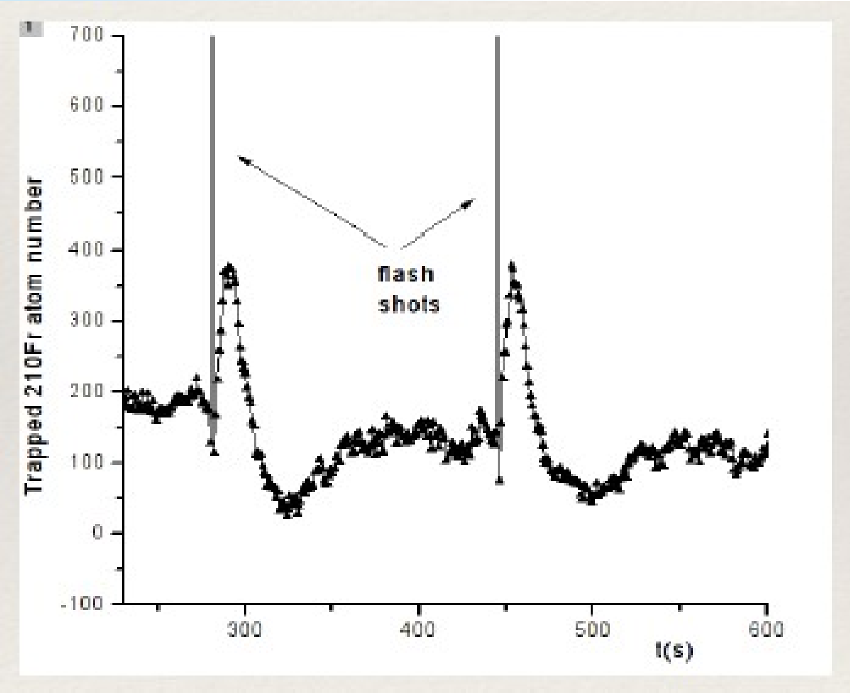
Rb MOT loading from OTS





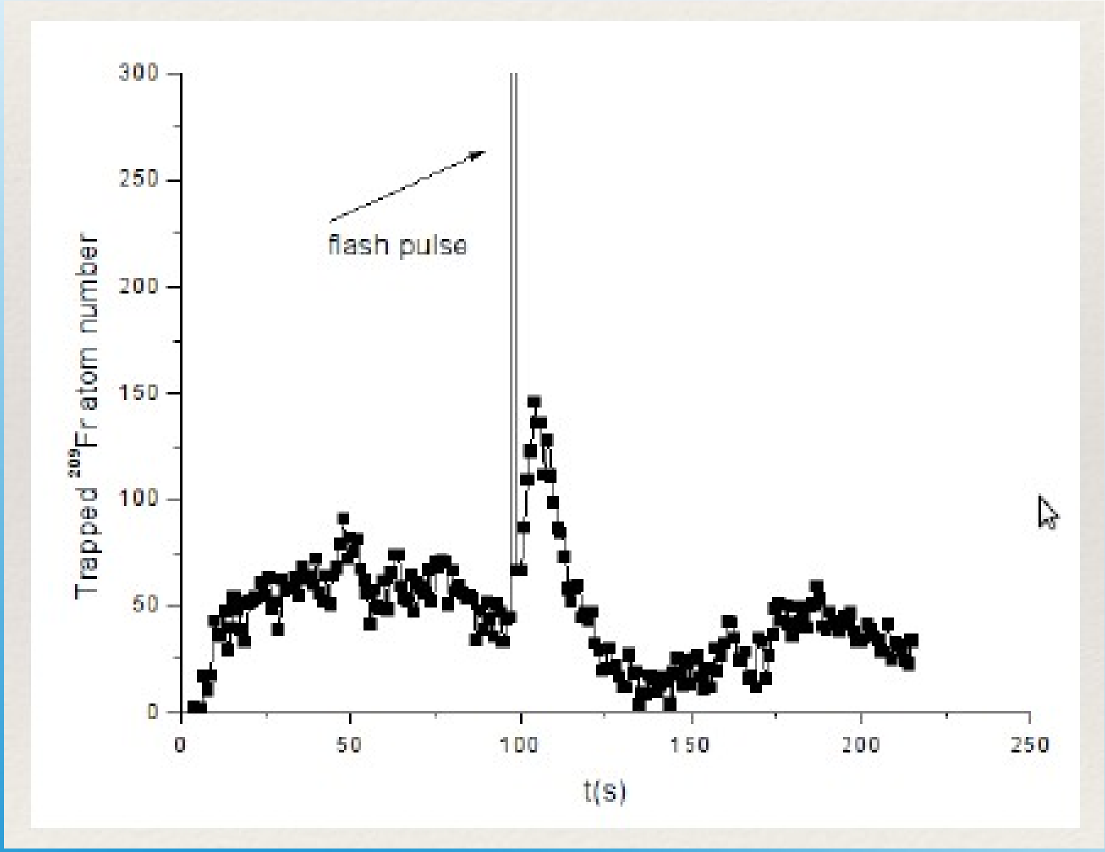
^{210}Fr MOT loading from PDMS





Scientific Reports

^{209}Fr MOT loading from PDMS



Scientific Reports

MOT dynamics

$$N_t(t) = \frac{LI_n}{CW} + A_1 e^{\gamma_+ t} + A_2 e^{\gamma_- t} +$$
$$+ LI_{Liad}\left(\frac{1}{\gamma_+\gamma_-} + \frac{e^{\gamma_+(t-t_0)}}{\gamma_+(\gamma_+ - \gamma_-)} + \frac{e^{\gamma_-(t-t_0)}}{\gamma_-(\gamma_- - \gamma_+)}\right)\Theta(t - t_0)$$

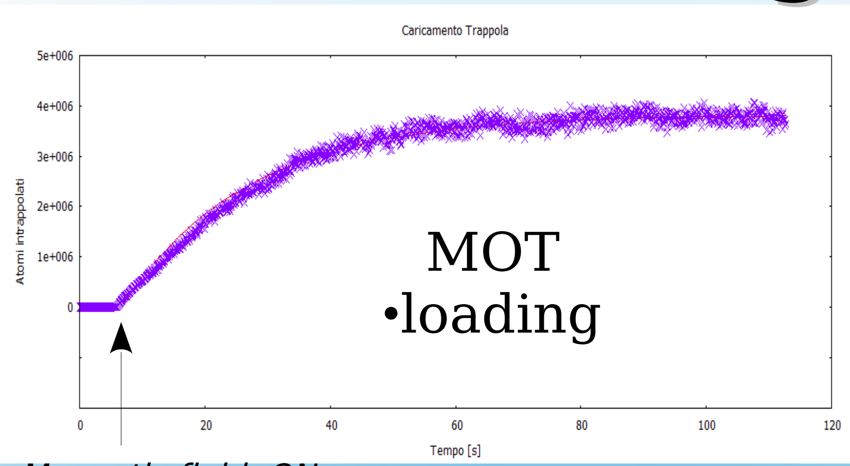
$$\begin{cases} \gamma_+ = \dfrac{-(C+W+L) + \sqrt{(C+W+L)^2 - 4CW}}{2} \\ \gamma_- = \dfrac{-(C+W+L) - \sqrt{(C+W+L)^2 - 4CW}}{2} \end{cases}$$

$$L \ll W$$

$$\gamma_+ \sim -C$$

$$\gamma_- \sim -W$$

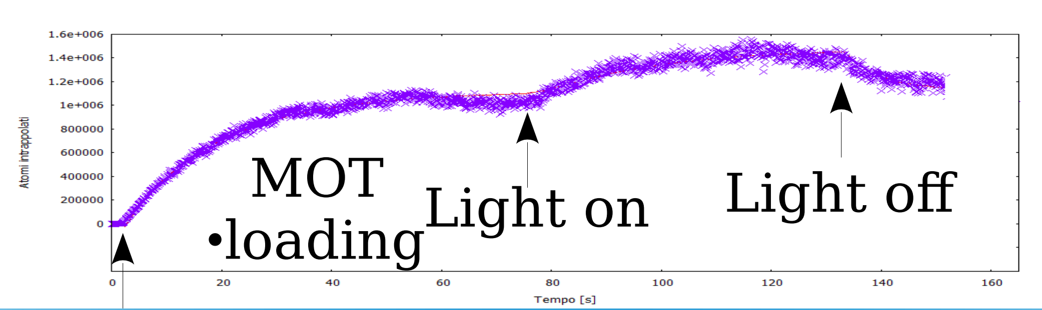
Fitting the curves



Magnetic field: ON
t = 6s

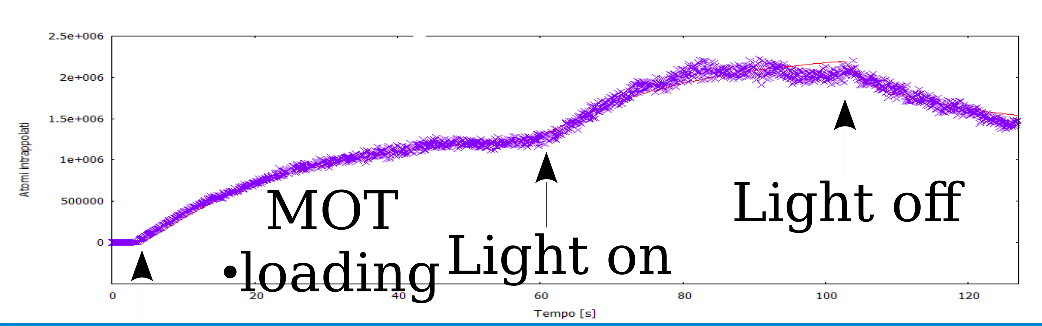
$$C = (5,04 \pm 0,08) \times 10^{-2}\ s^{-1}$$

$$W = 0,74 \pm 0,06\ s^{-1}$$

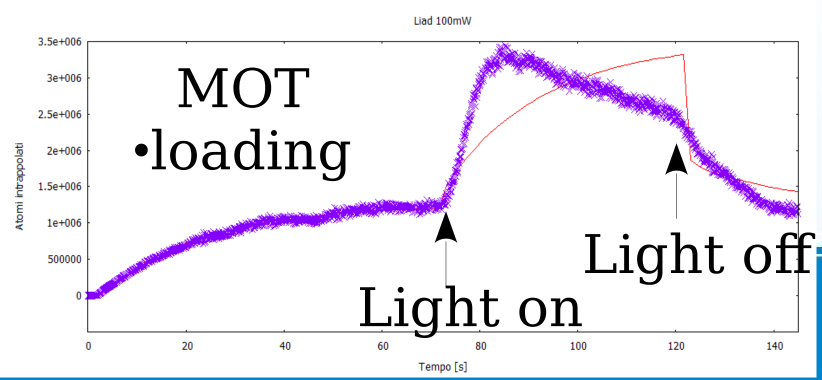


Magnetic field: ON

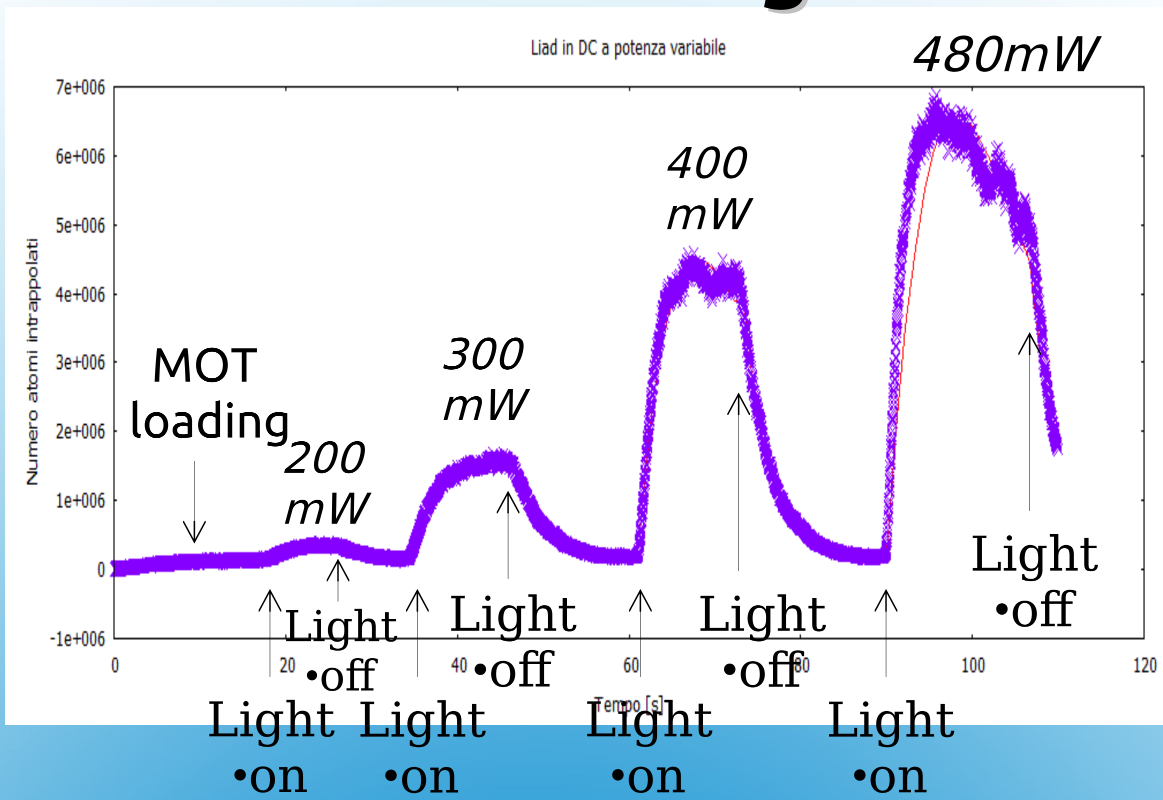
Simulation curves are in red
•(if you are able to see)

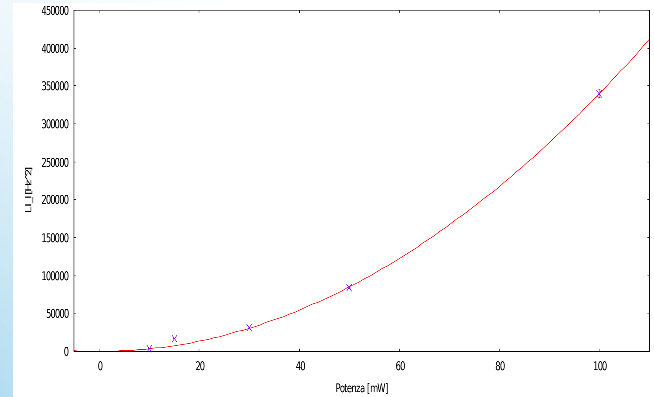


Magnetic field: ON



Fitting the curves





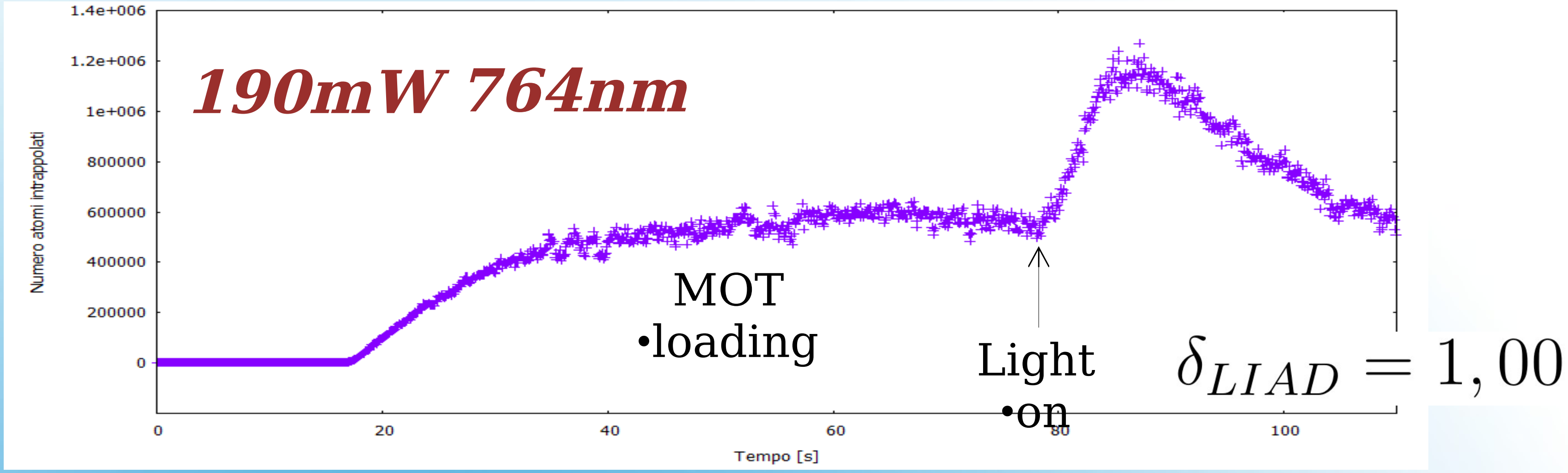
"Millennia" laser @532 nm used as a desorption light

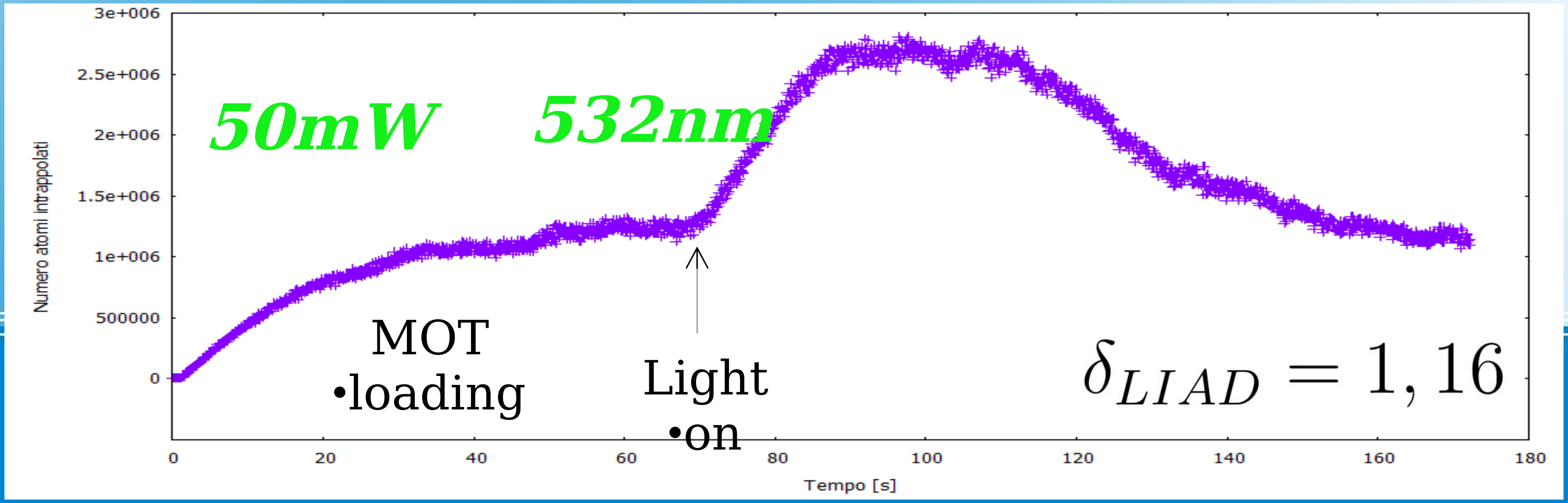
$$I_{Liad}(t) = I_{Liad}\, e^{\frac{-t}{\tau}} \approx I_{Liad}\left(1 - \frac{t}{\tau}\right)$$

$$C(t) = C_0\left(1 + \frac{t}{\tau_c}\right)$$

$$\gamma_+ \longrightarrow \gamma_+(t)$$

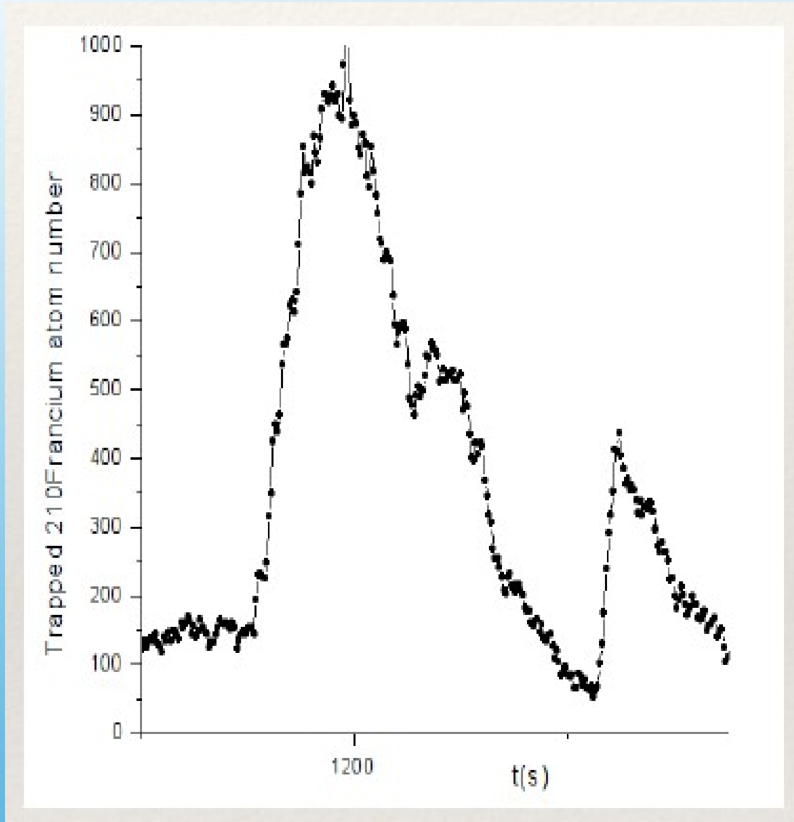
Higher the frequency, higher the rate

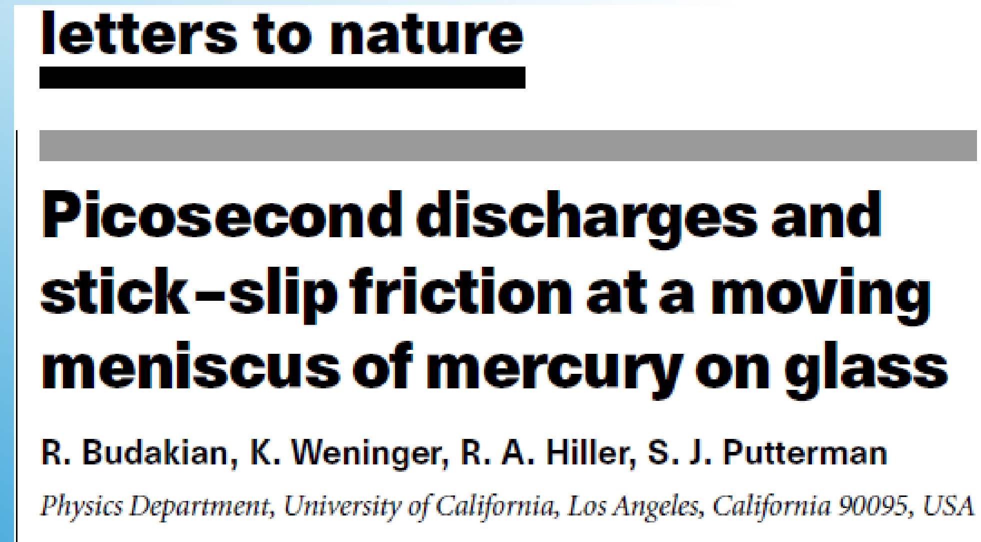




V. Coppolaro et al., J. Chem. Phys. 141, 134201 (2014)

SURPRISING...




letters to nature

Picosecond discharges and stick–slip friction at a moving meniscus of mercury on glass

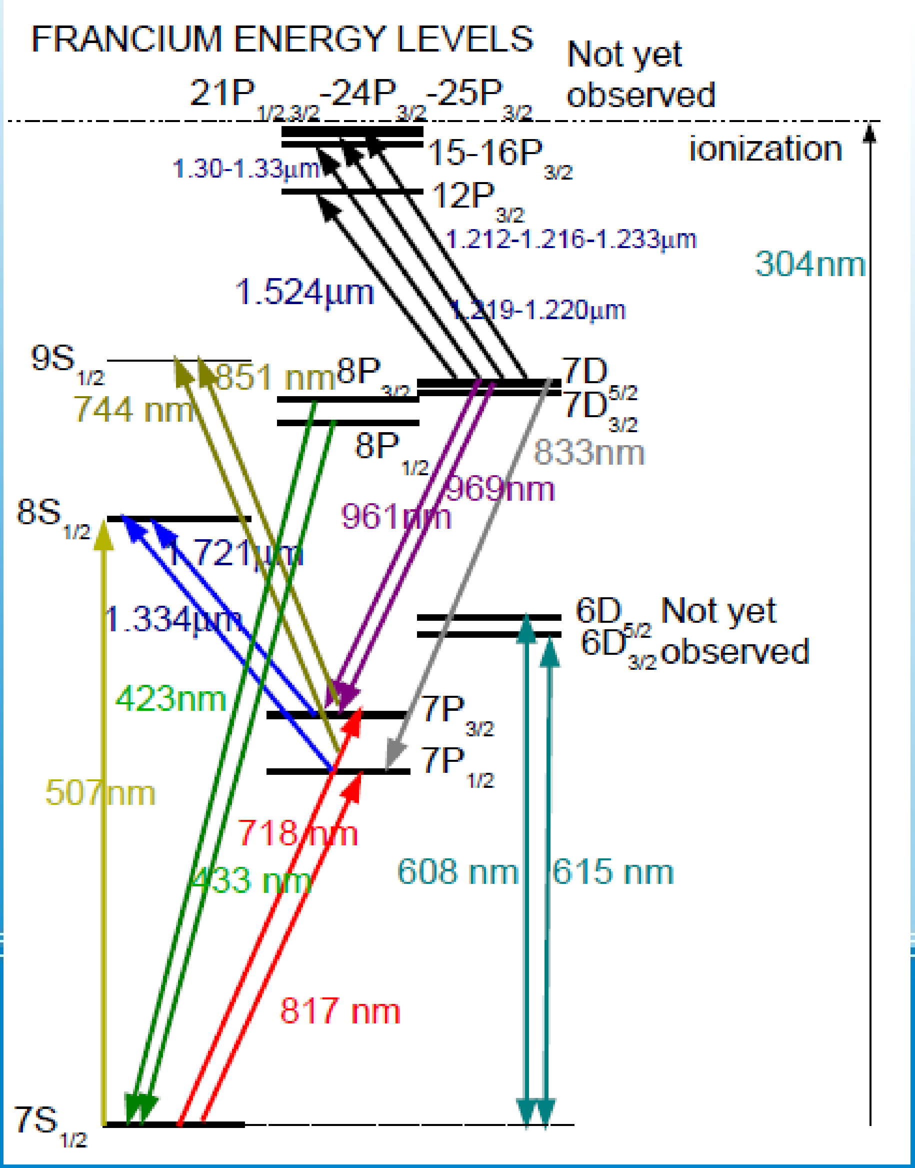
R. Budakian, K. Weninger, R. A. Hiller, S. J. Putterman

Physics Department, University of California, Los Angeles, California 90095, USA

Scientific Reports 2017

PERSPECTIVES

New spectroscopic measurements



New spectroscopic measurements

- ENERGY LEVEL DETERMINATION
- LIFETIMES MEASUREMENTS
- COLLISIONAL STUDIES
- DIMER FORMATION