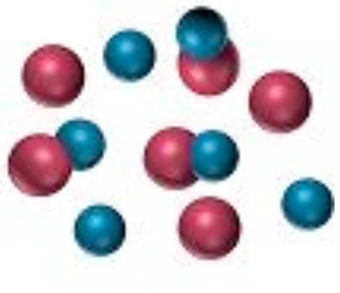
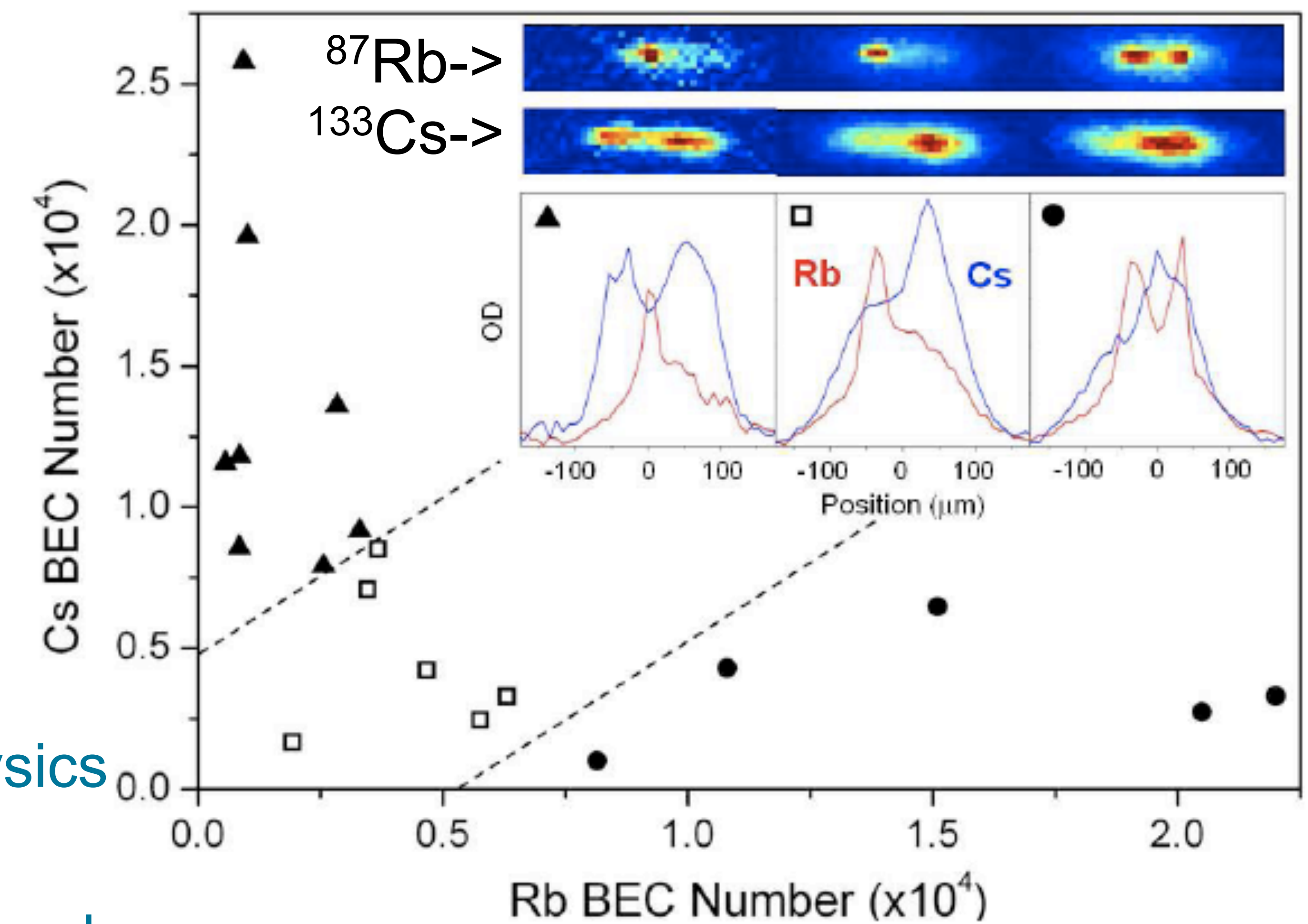
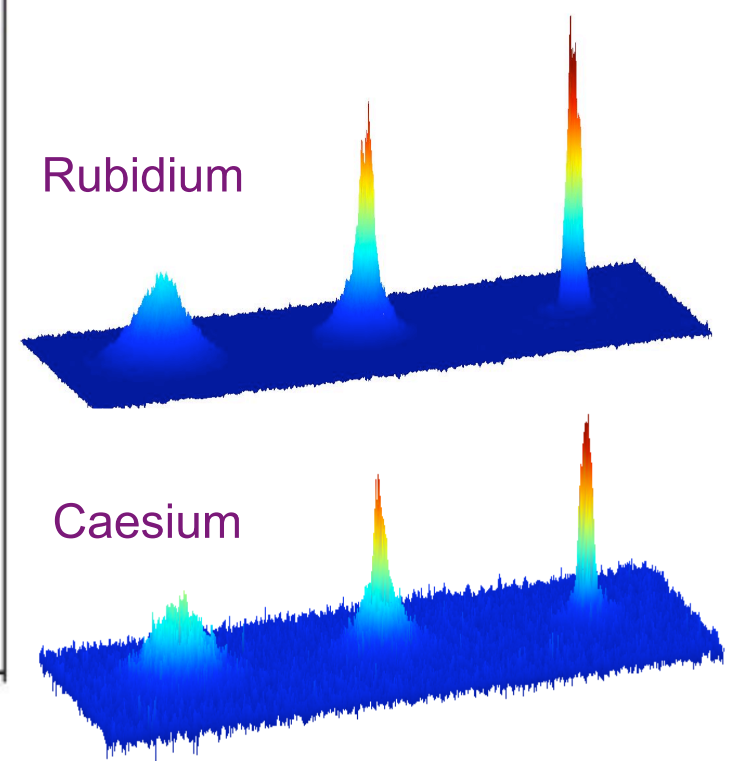


A Quantum Degenerate Bose Mixture of ^{87}Rb and ^{133}Cs -Toward Ultracold Heteronuclear Molecules

D. J. McCarron, D. L. Jenkin, M. P. Köppinger, K. L. Butler, H. W. Cho, and S. L. Cornish





Department of Physics
Durham University

http://massey.dur.ac.uk

Motivation

- Bialkali molecules in the ground state have a large permanent electric dipole moment

ex. RbCs d=1.25 Debye

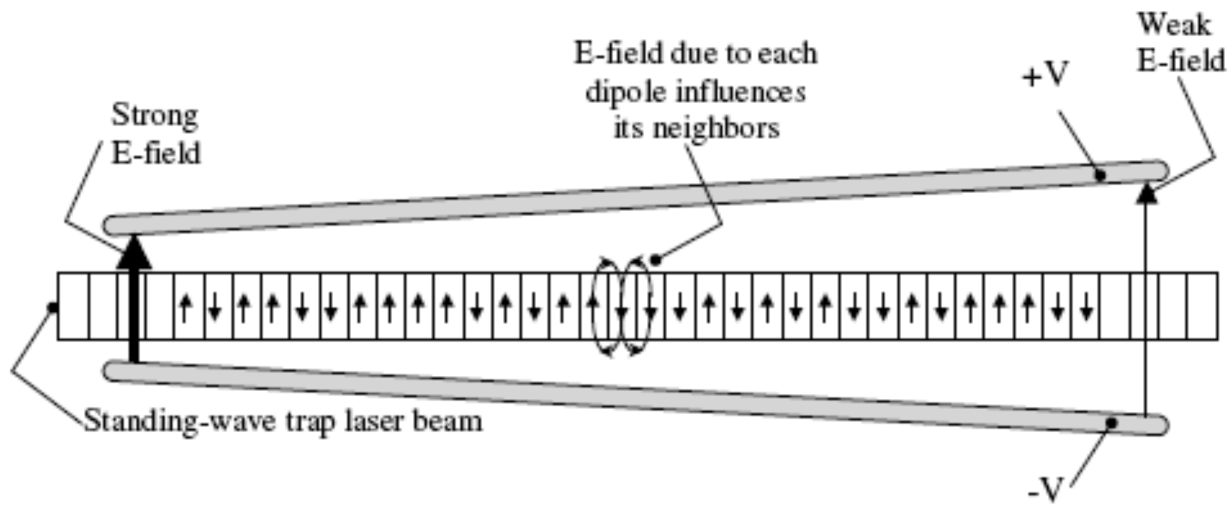
$$V_{int} = d^2 \frac{1 - 3cos^2\theta}{|\vec{r} - \vec{r'}|^3} + \frac{4\pi\hbar^2 a}{M}\delta(\vec{r} - \vec{r'})$$

Dipole-dipole interaction

Contact interaction

^{52}Cr BEC_PRL, 101, 080401 (2008)

- Quantum computation with trapped polar molecules



PRL, 88, 067901 (2002)

- RbCs is one of the stability of quantum gases of alkali-metal dimers

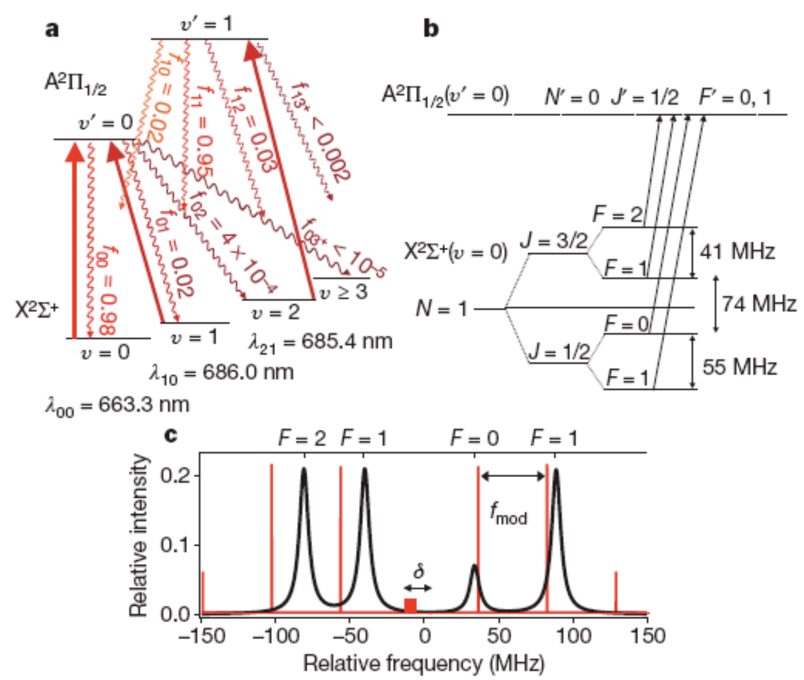
ex.
XY+XY→X_2+Y_2
XY+XY→X+XY_2 or X_2Y+Y

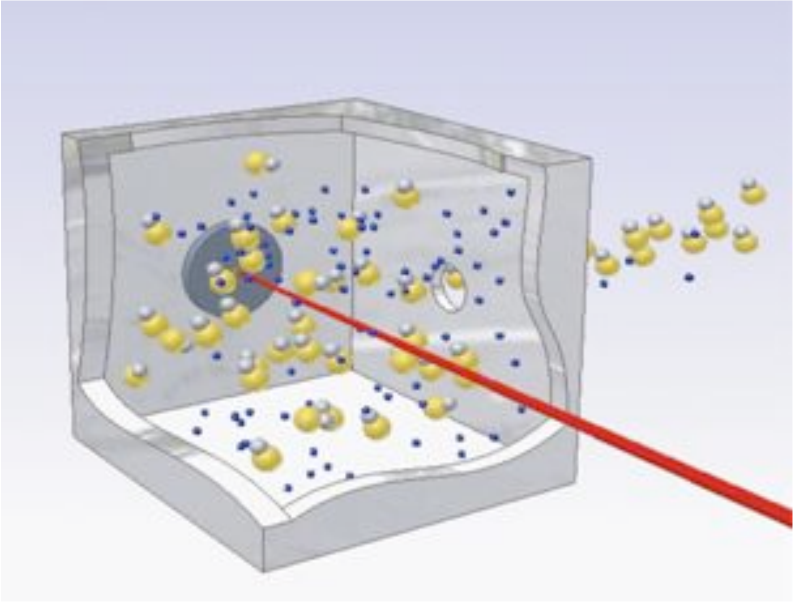
	Na	K	Rb	Cs
Li	−328(2)	−533.9(3)	−618(200)	−415.38(2)
Na		74.3(3)	45.5(5)	236.75(20)
K			−8.7(9)	37.81(13)
Rb				29.1(1.5)

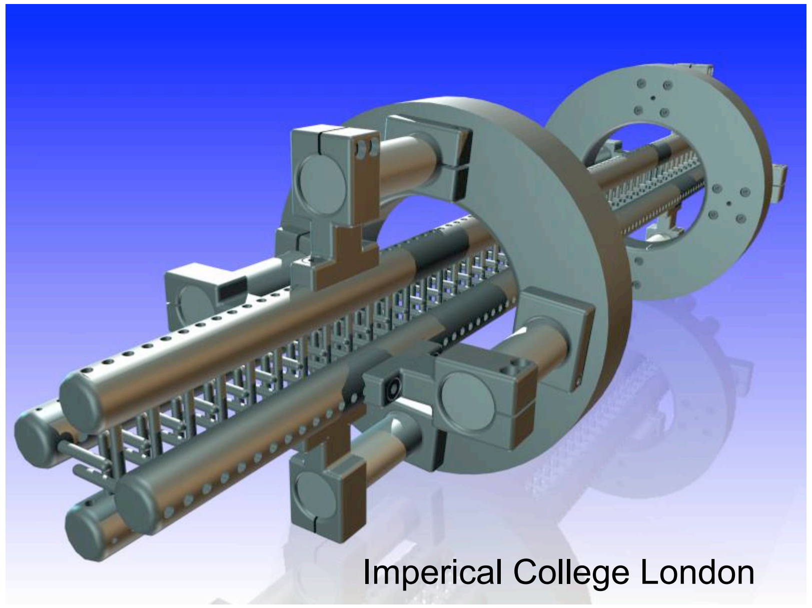
PRA, 81, 060703(R) (2010)

Cool Molecules

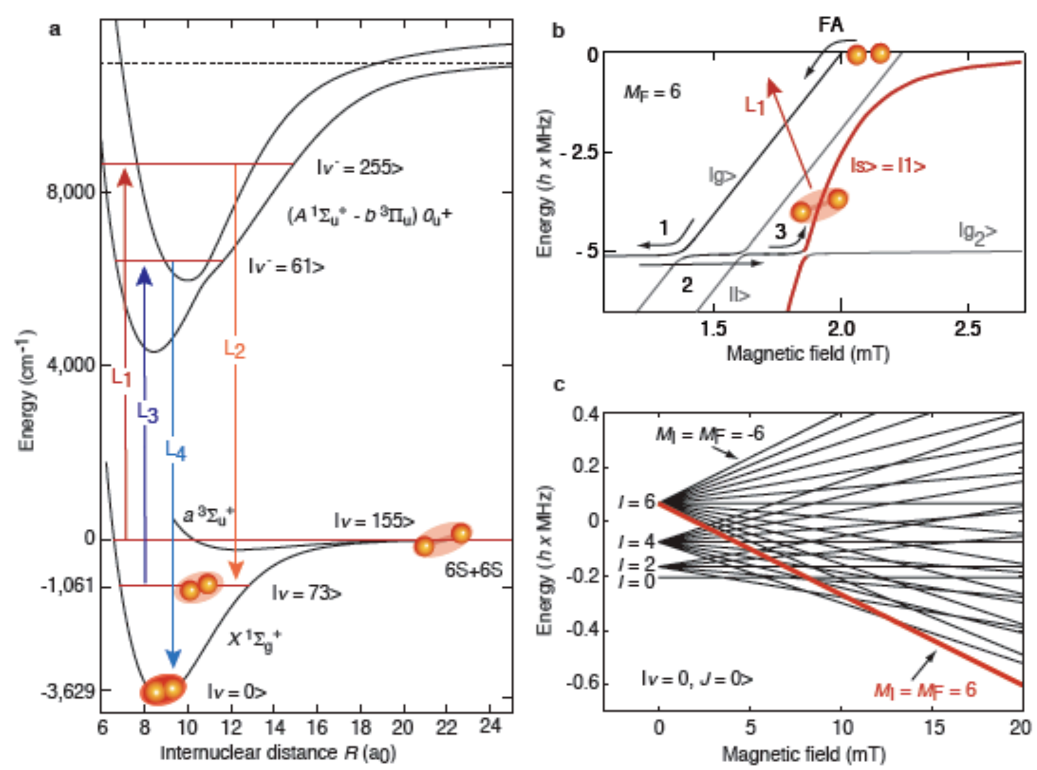
Directly:
Buffer gas cooling
Stark deceleration_Electric & Magnetic
Sympathetic cooling
Laser-cooling Nature, 467, 820 (2010)







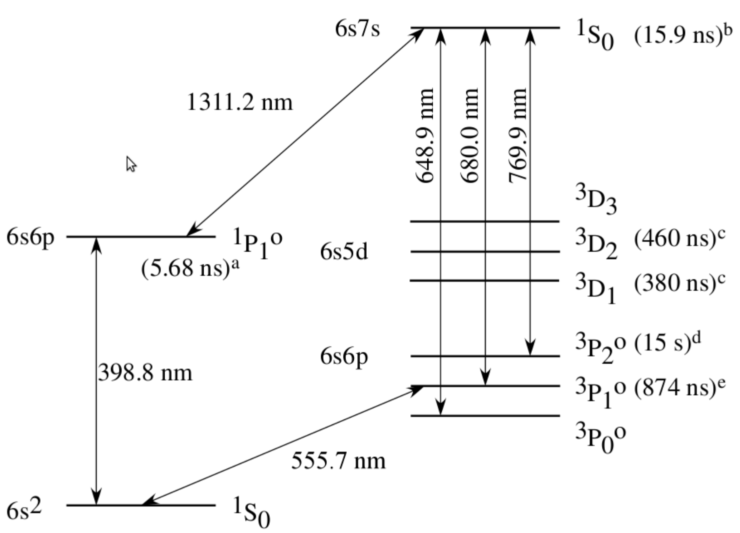
Indirectly:
Atoms are pre-cooled by laser-cooling and then,
1) associated into ground state via photoassociation
or
2) follow a two step scheme which is magneto-association using a Feshbach resonance and STIRAP



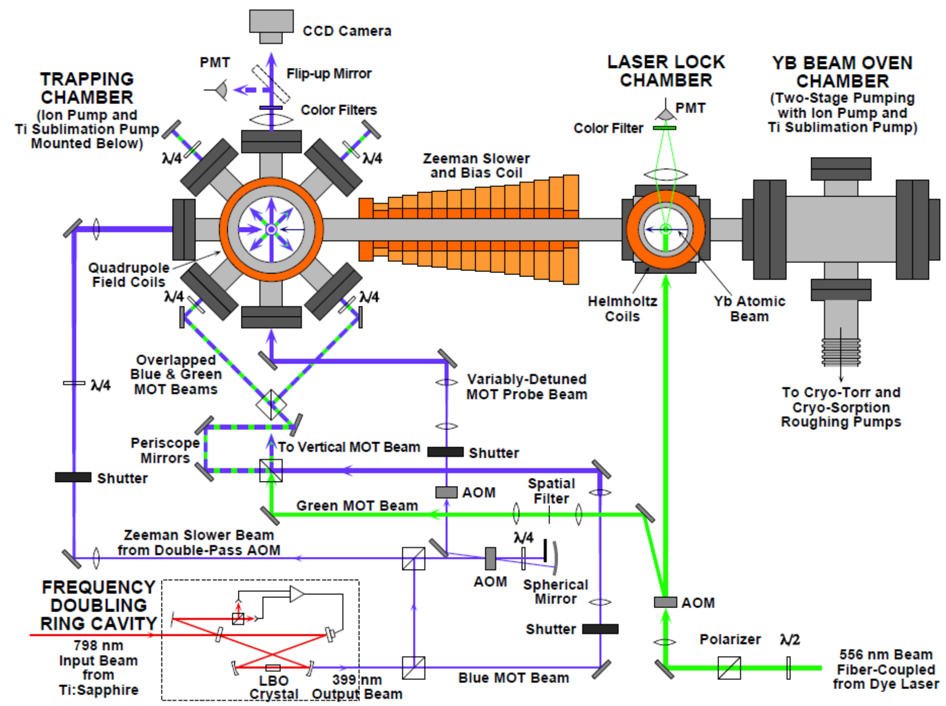
Nature Physics, 6, 265-270 (2010)

MMQA_MicroKelvin Molecules in a Quantum Array

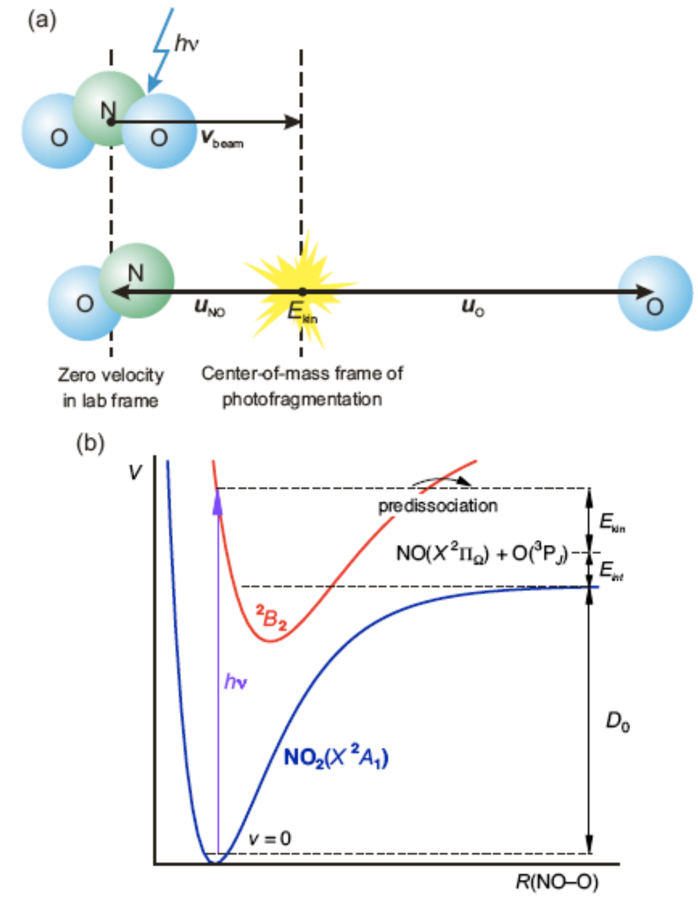
Professor EA Hinds (Physics ICL)
Dr D Carty (Physics & Chemistry Durham)
Dr SL Cornish (Physics Durham)
Professor JM Hutson (Chemistry Durham)
Dr MR Tarbutt (Physics ICL)
Dr E Wrede (Chemistry Durham)



Rapol U.D. et al, 2004, *Eur. Phys. J. D.*, **29**, 409
Baumer F., 2010, Thesis, Dusseldorf



Maruyama R., 2003, Thesis, Washington



arXiv:1002.3698v1

- Magnetic deceleration
- CsYb molecules via magneto-association and STIRAP
- Theory of ultracold molecule formation, cooling molecules to microkelvin using the theory of ultracold collisions to make sympathetic cooling work
- Buffer gas cooling, electric deceleration, and sympathetic cooling.
- Photostop

Introduction

Atoms in which laser cooling has been demonstrated[1]:

Alkali metals	Alkaline earth metals	Noble Gases	Lanthanide	Others
Li	Mg	He	Dy	Cr
Na	Ca	Ne	Er	Ag
K	Sr	Ar	Tm	Cd
Rb	Ra	Kr	Yb	Hg
Cs	Ba	Xe		Al
Fr				

Species	Dipole Moment
^{6}Li^{23}Na	0.53 D[4]
^{40}K^{87}Rb	0.57 D[2]
^{87}Rb^{133}Cs	1.25 D[3]
^{6}Li^{40}K	3.5 D[4]
^{6}Li^{87}Rb	4.1 D[4]
^{6}Li^{133}Cs	5.48 D[4]

Mixed species Feshbach molecules:

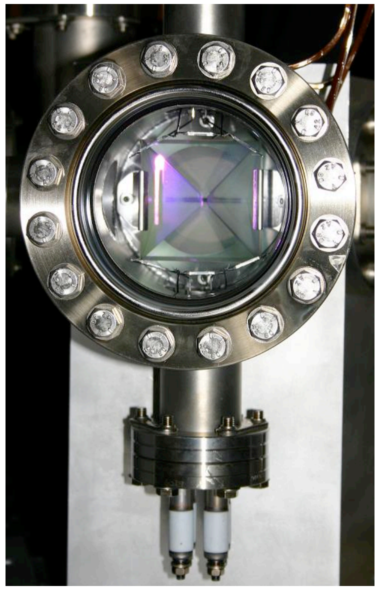
^{6}Li + ^{23}Na (Stan *et al.*, Phys. Rev. Lett. 93, 143001 (2004))
^{40}K + ^{87}Rb (Inouye *et al.*, Phys. Rev. Lett. 93, 183201 (2004))
^{6}Li + ^{40}K (Wille *et al.*, Phys. Rev. Lett. 100, 053201 (2008))
^{6}Li + ^{87}Rb (Deh *et al.*, Phys. Rev. A 77, 010701(R) (2008))
^{7}Li + ^{87}Rb (Marzok *et al*. Phys. Rev. A 79, 012717 (2009))
^{87}Rb + ^{133}Cs (Cho et al. EPJD accepted 2011; Pilch *et al*. Phys. Rev. A 79, 042718 (2009))

[1](Steele, J. Vac. Sci. Technol. B 28, C6F1 (2010))
[2](Ni *et al.*, Science 322, 231 (2008))
[3](Kotochigova *et al.*, J. Chem. Phys. 123, 174304 (2005) theor.)
[4](Igel-Mann *et al.*, J. Chem. Phys. 84, 5007 (1986) theor.)

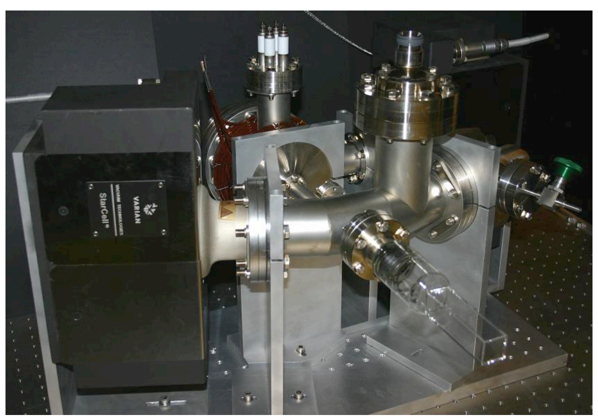
Outline

- Bose-Einstein condensation of ^{87}Rb BEC
  - in a combined magnetic and optical trap
  - in a levitated crossed dipole trap
- Bose-Einstein condensation of ^{133}Cs
  - a new method for the production of ^{133}Cs BEC
  - demonstrate the creation of Cs_2 molecules via magneto-association on the 4g(4)
- A quantum degenerate Bose Mixture of ^{87}Rb and ^{133}Cs
  - observe a striking phase separation of the two species
  - observation of an interspecies Feshbach resonance at 181.7(5) G
- Stimulate Raman adiabatic passage (STIRAP)
  - a two-photon transition can used to transfer the Feshbach molecules into the rovibrational ground state or a more deeply bound state
- Conclusion

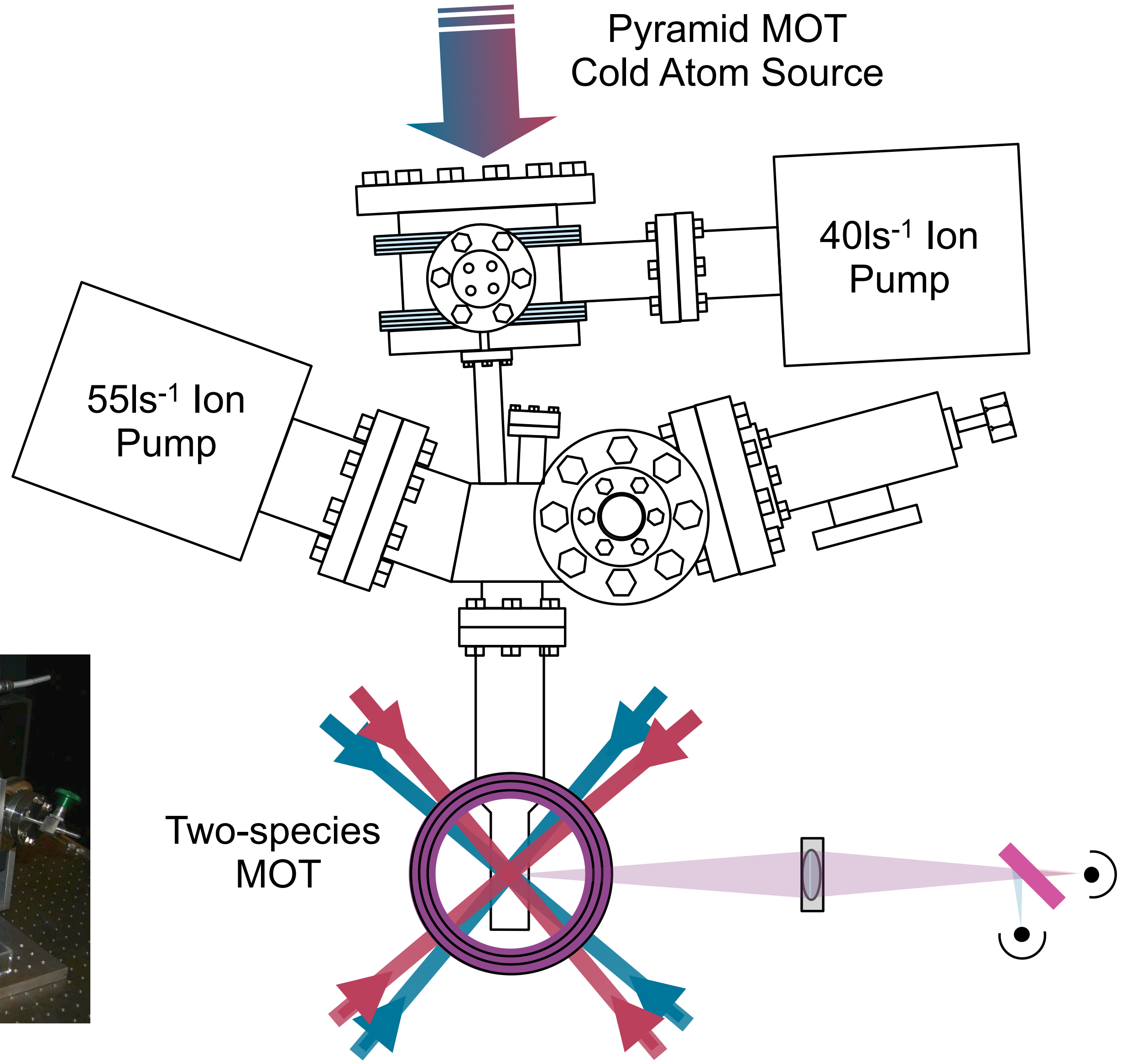
Review

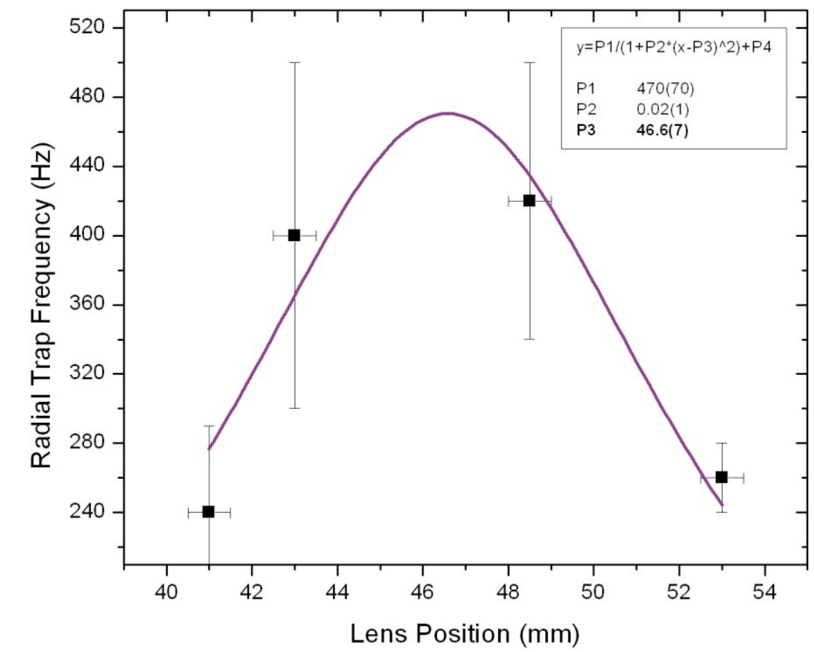


Pyramid Chamber



Vacuum System





- Cold-atomic beams source is created by Pyramid MOT.
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Review

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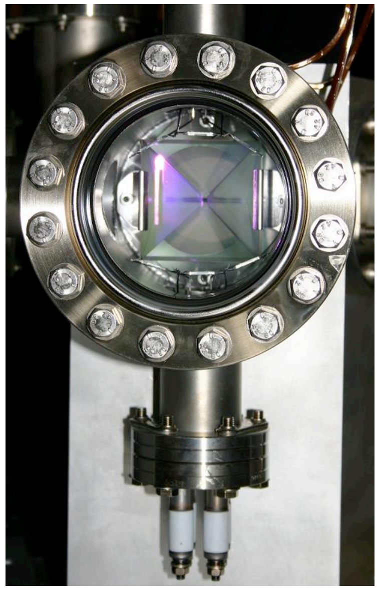

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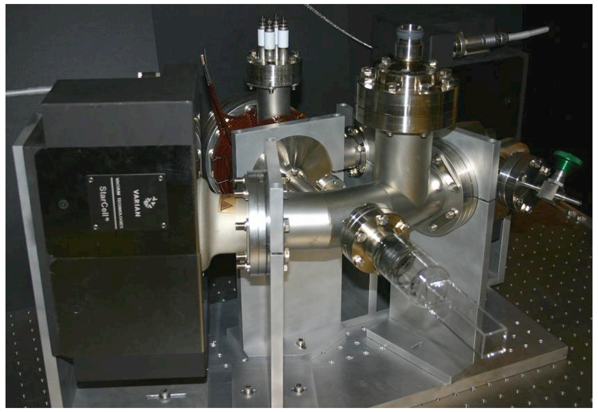

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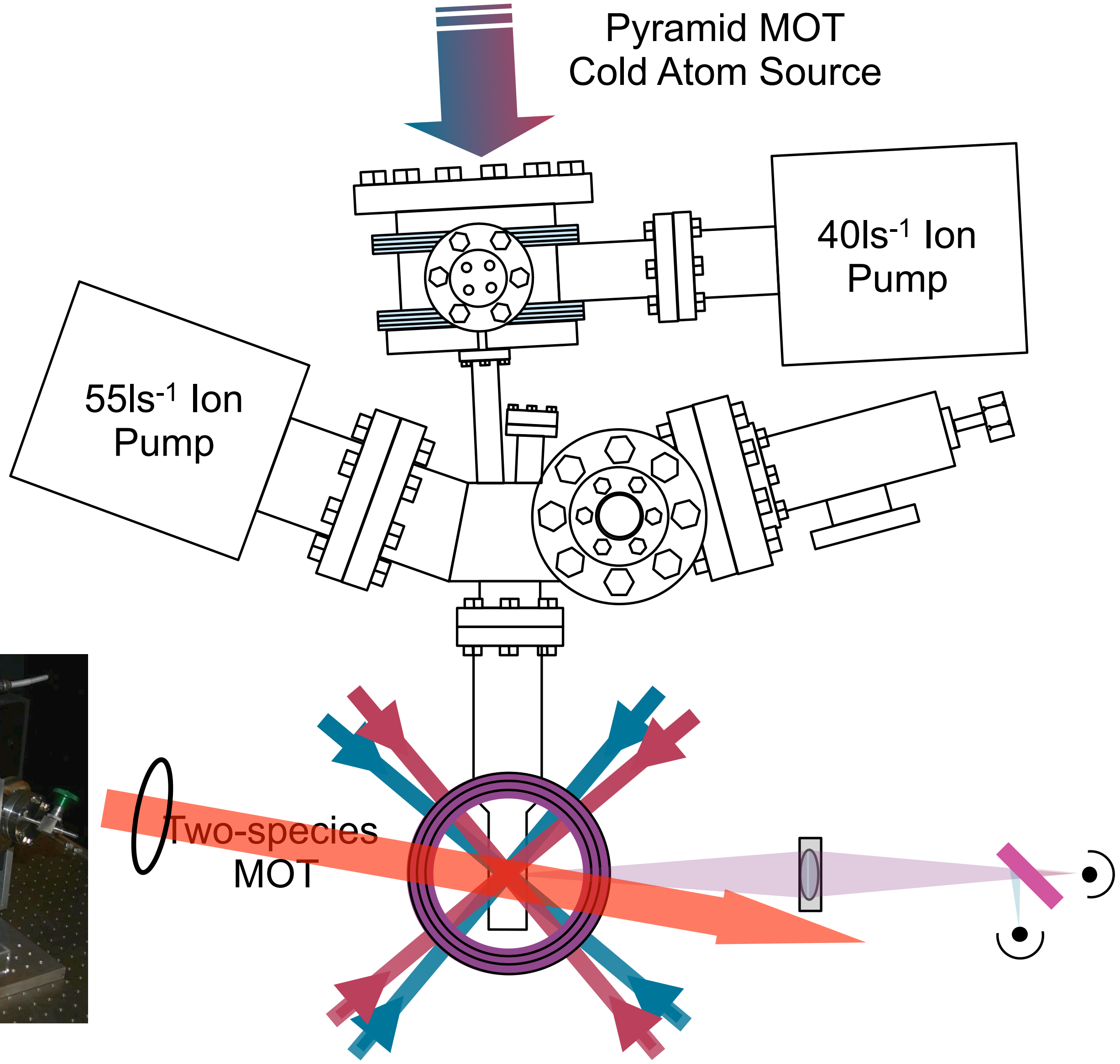

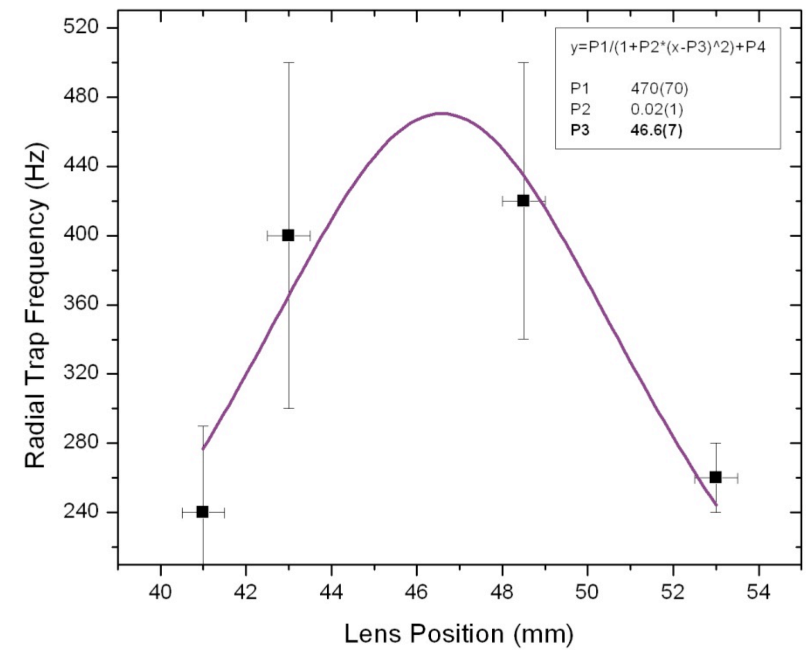

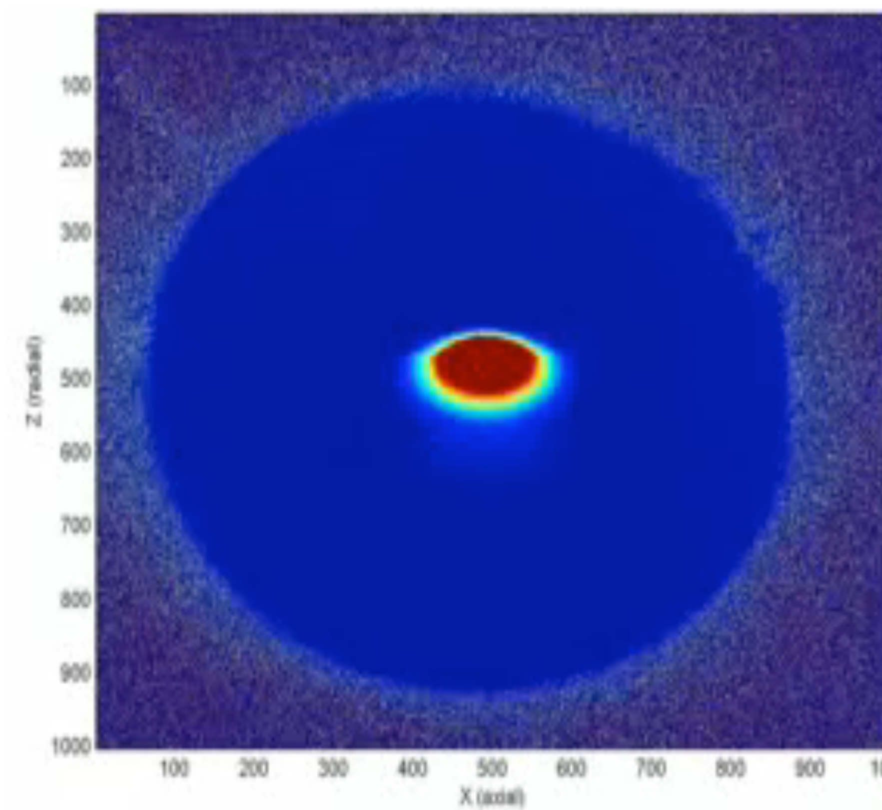

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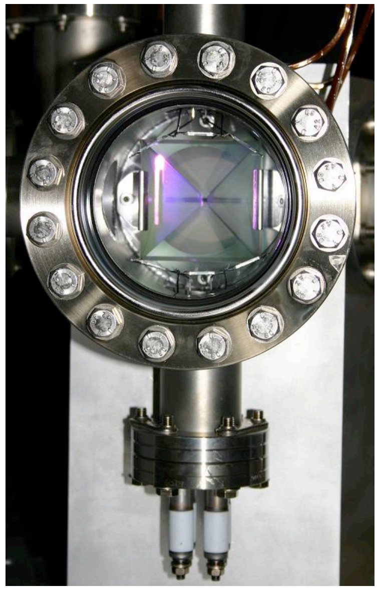

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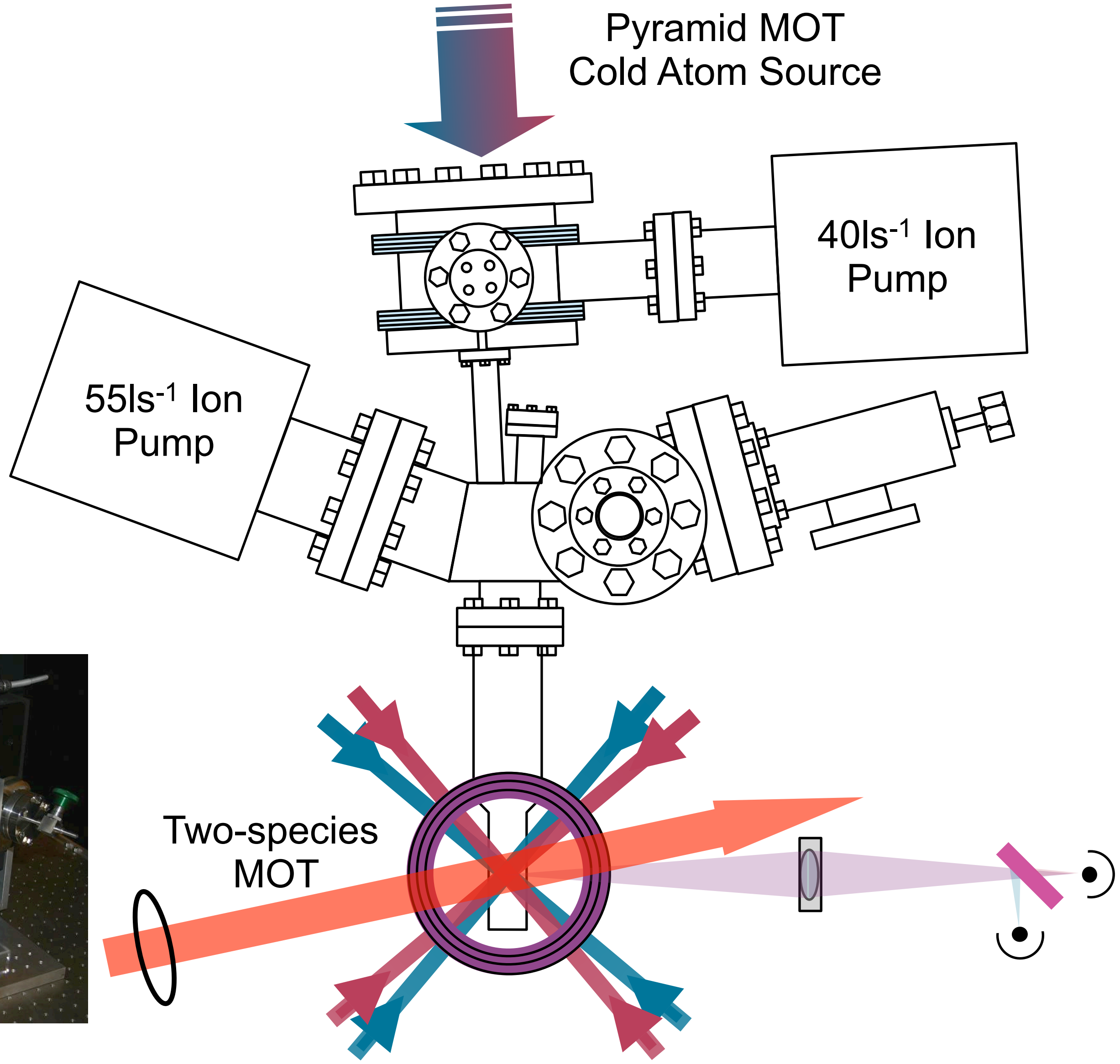

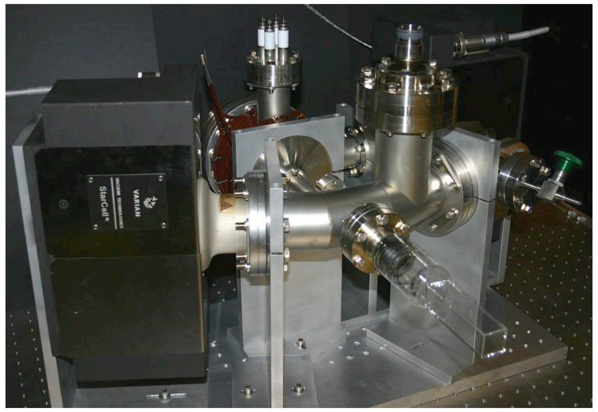

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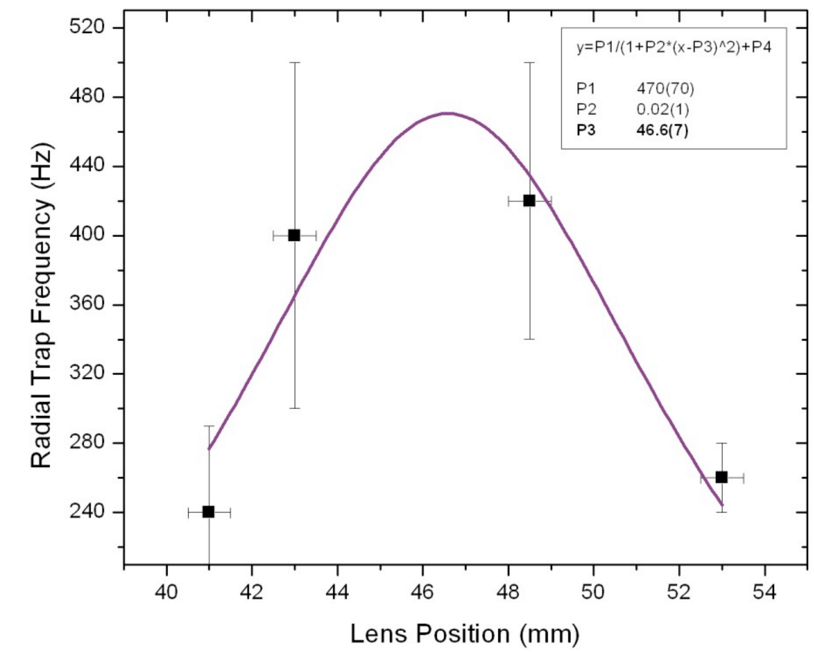

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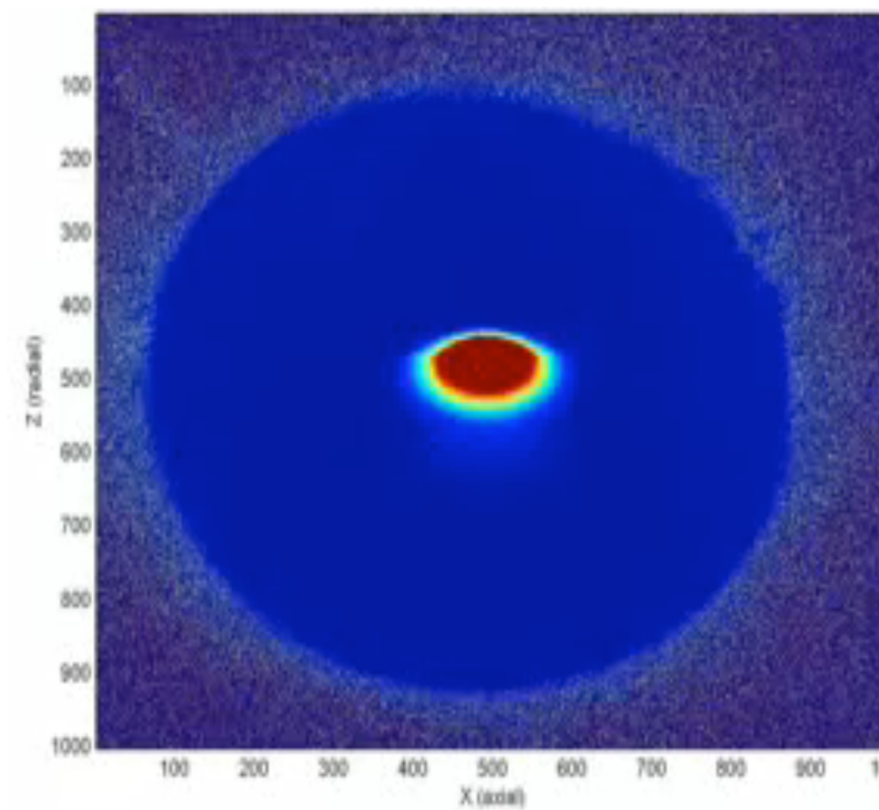

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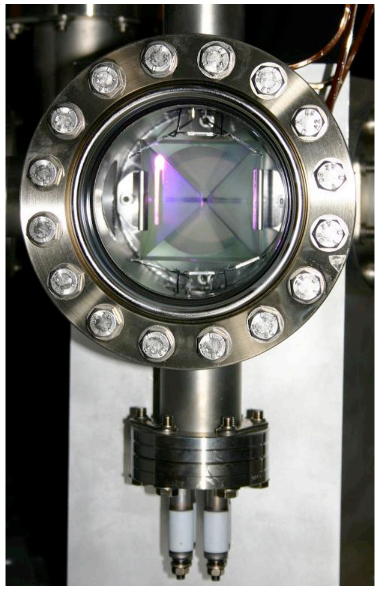
Review



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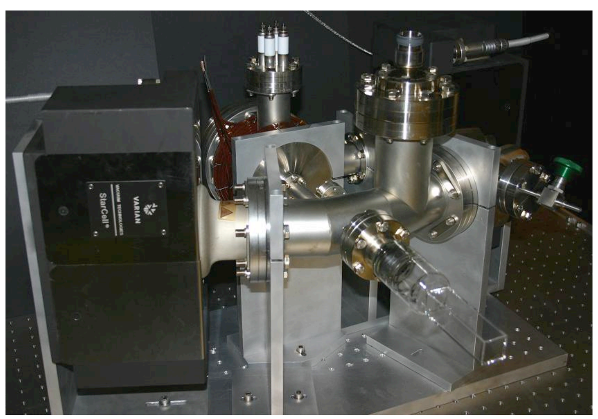

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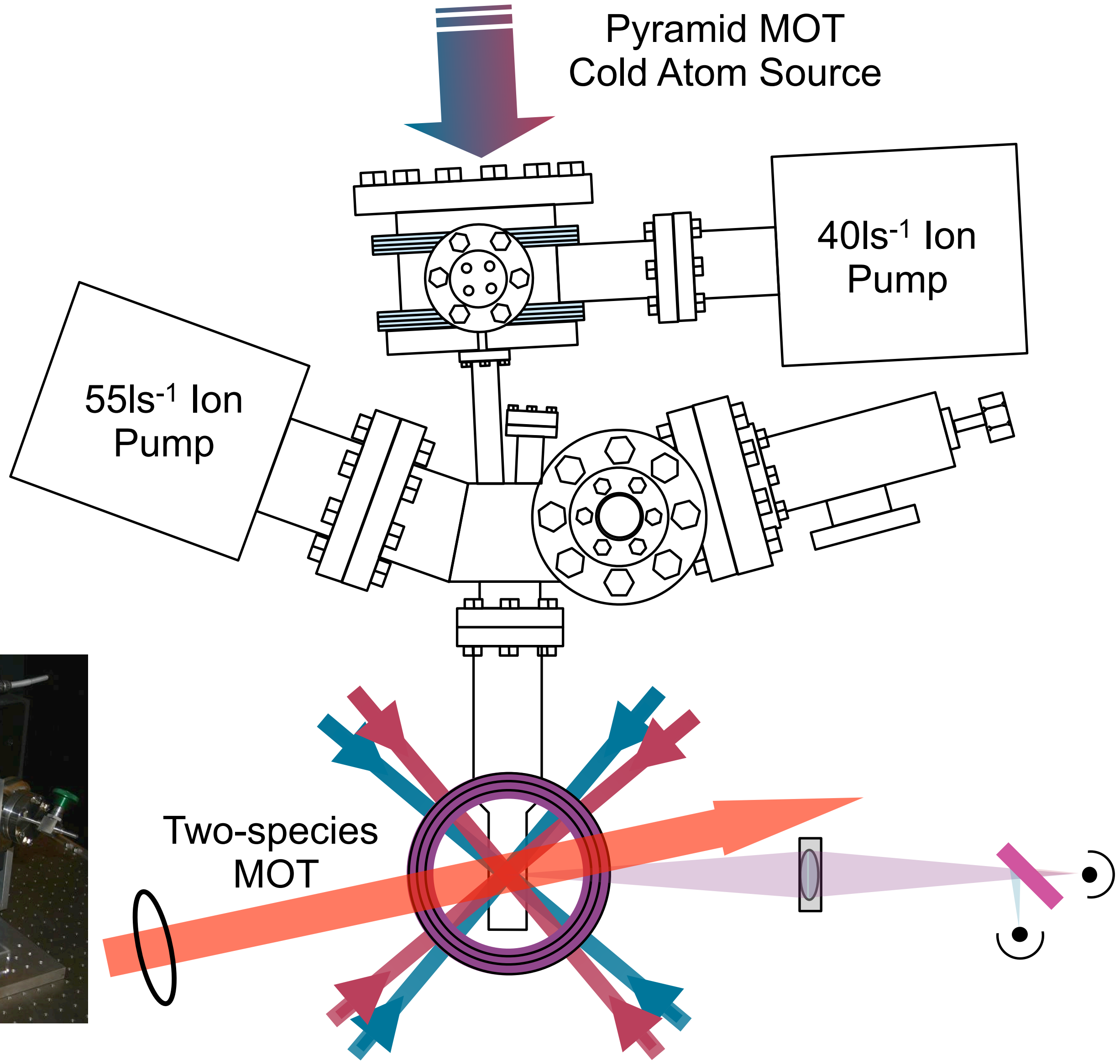

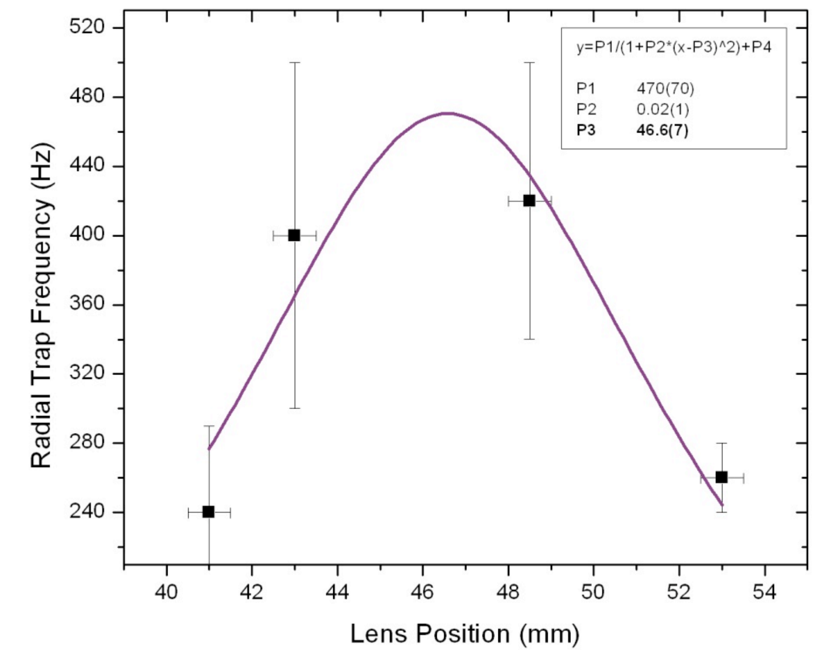

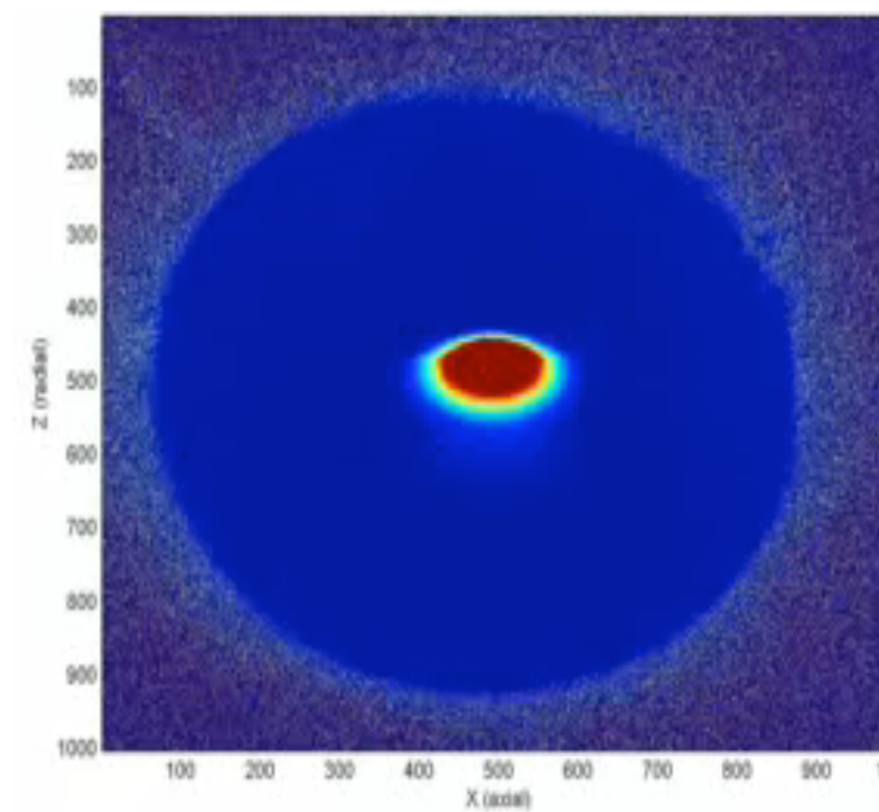

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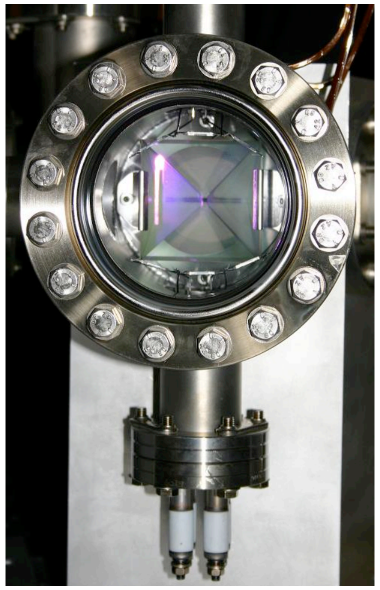

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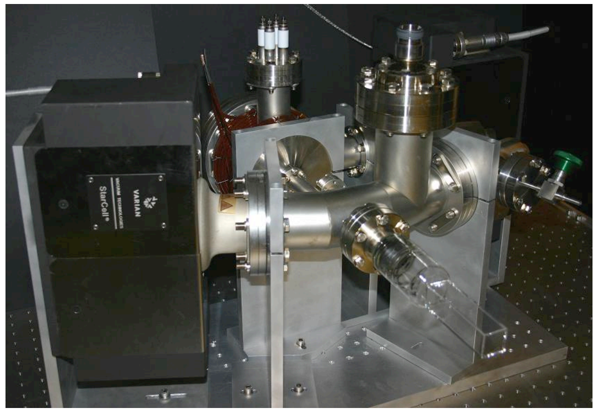

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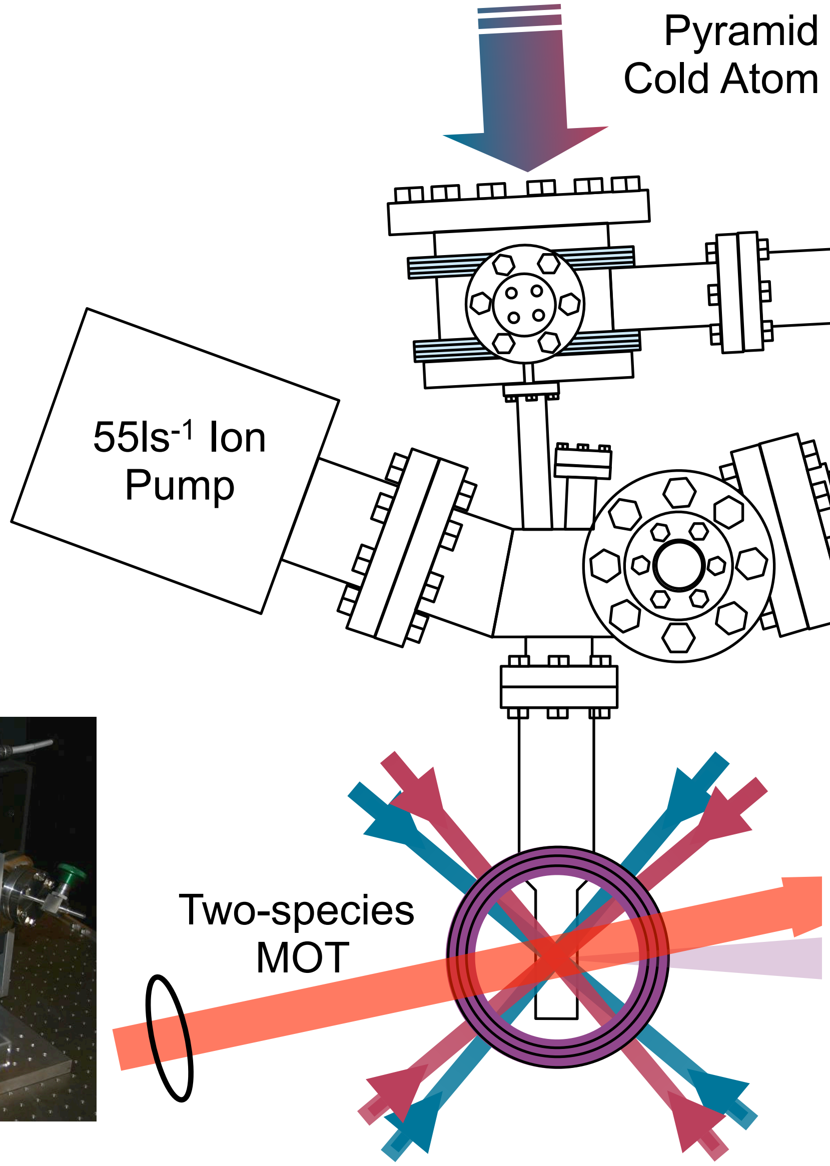

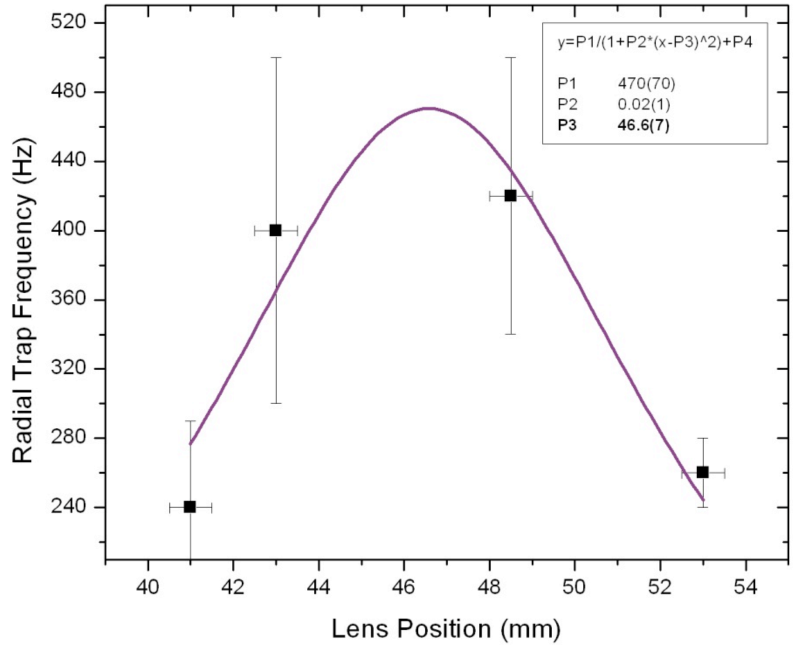

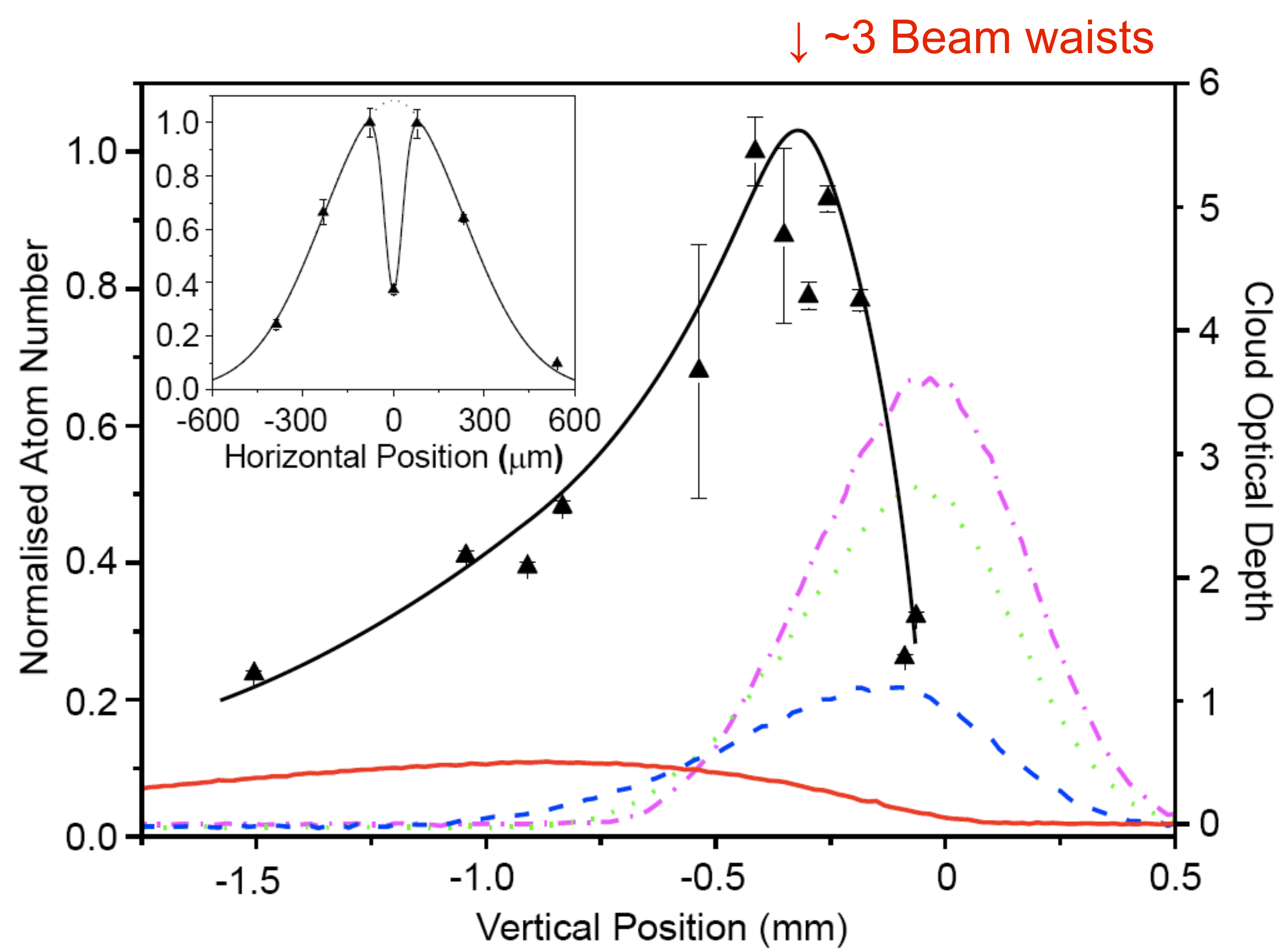

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^{87}Rb BEC in a combined trap

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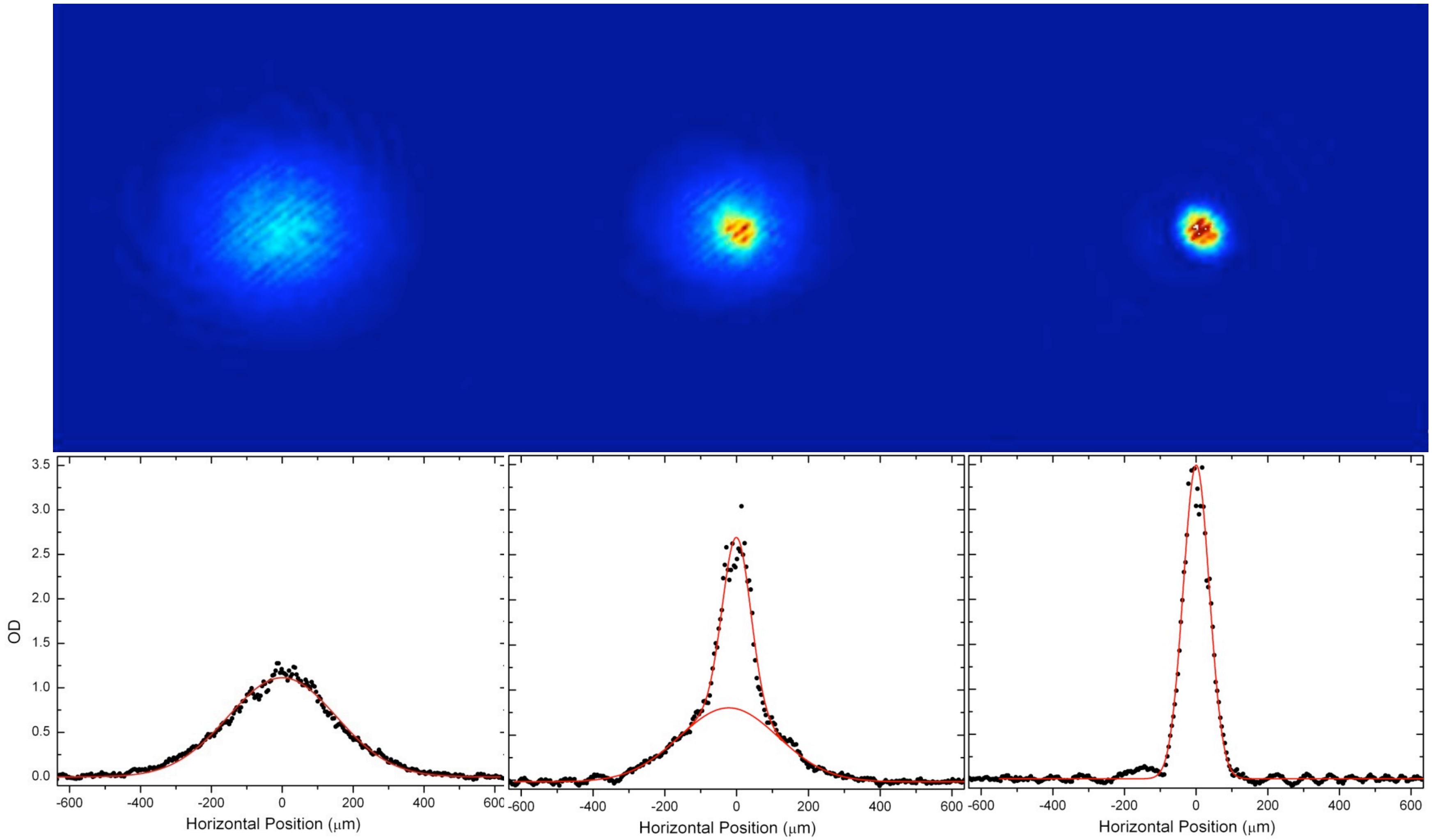
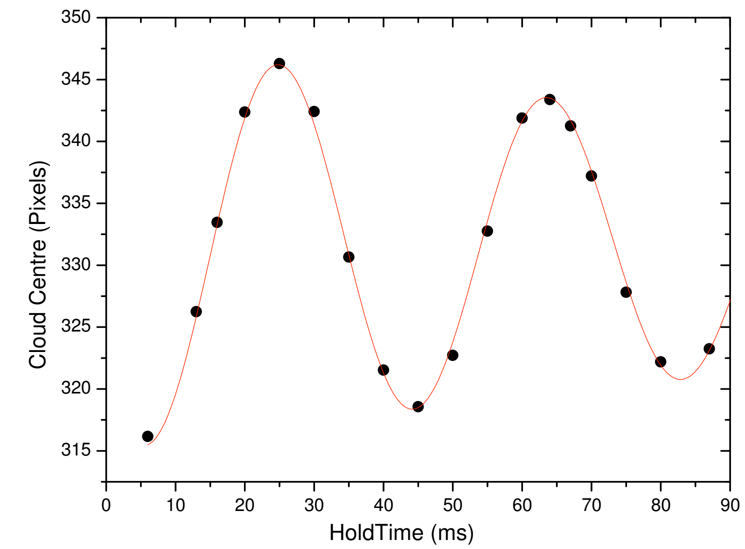
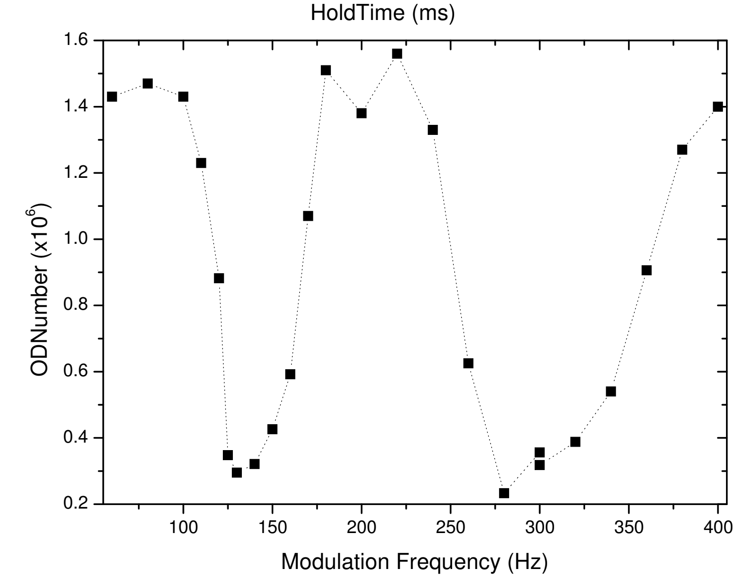






P = 502 mW
Waist = 62 μm
U = 7.0 μK
ω_z = 25.8 Hz
ω_ρ = 136.8 Hz
T_{Mean} = 0.371 μK
N = 1.11 x 10^6
n_0 = 4.41 x 10^{13} cm^{-3}
PSD = 1.06

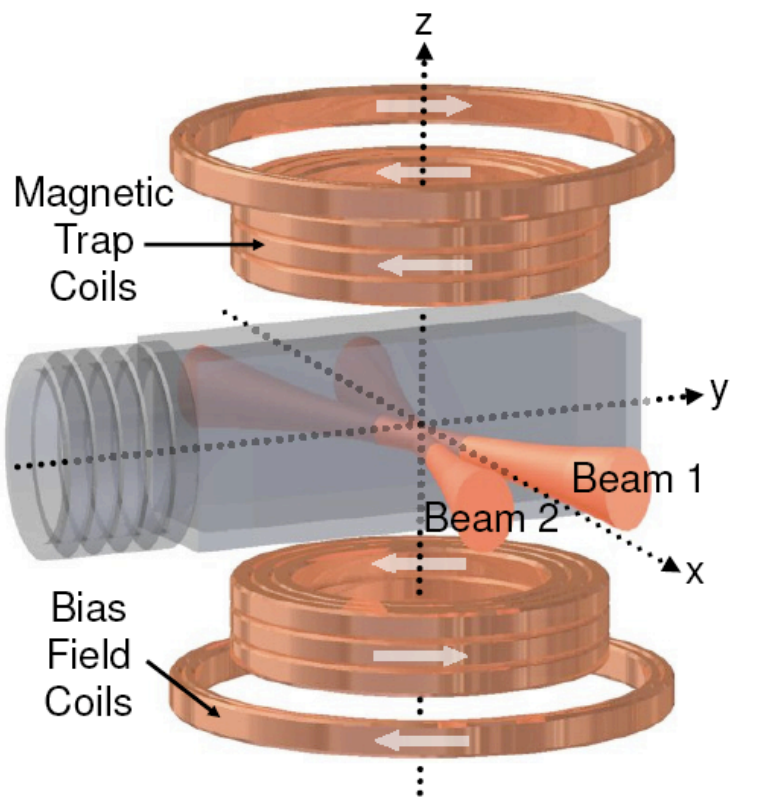
P = 389 mW
Waist = 62 μm
U = 5.3 μK
ω_z = 25.8 Hz
ω_ρ = 120.7 Hz
T_{Mean} = 0.252 μK
N = 7.01 x 10^5
N_0/N = 14.6 %
PSD = 1.51

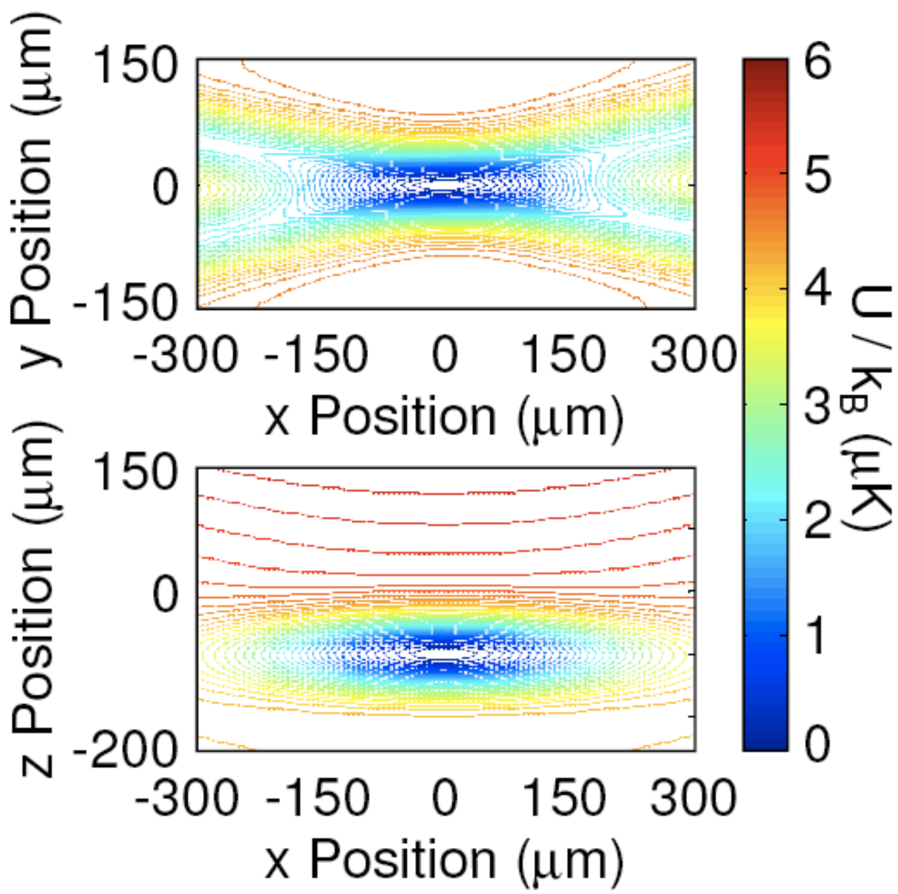
P = 252 mW
Waist = 62 μm
U = 3.3 μK
ω_z = 25.8 Hz
ω_ρ = 97.8 Hz
N = 1.93 x 10^5
n_0 = 2.26 x 10^{14} cm^{-3}

^{87}Rb BEC in a levitated crossed dipole trap

- Atoms in the weak-field seeking |1,-1> state are loaded into the hybrid trap, a cross-dipole trap and quadrupole trap, after a pre-cooling using RF evaporation in quadrupole trap.
- The levitated crossed dipole trap is formed by two laser beams and a levitation field. The contour plots results the trapping potential including gravity for ^{87}Rb in the |1,+1> state. Both 150 mW beams are focussed to ~60 μm and the magnetic filed contents a magnetic field gradient 29 G/cm and a bias field of 22.4 G along z axial.

$\Delta U_{gravity} = mg\,(\Delta z)$
$\Delta E = \mu_F g_F m_F \Delta B_z$





- The loading trap is performed at a power of 6 W in each beam with a gradient of 29 G/cm.

Accepted by Eur. Phys. J. D, (2011)

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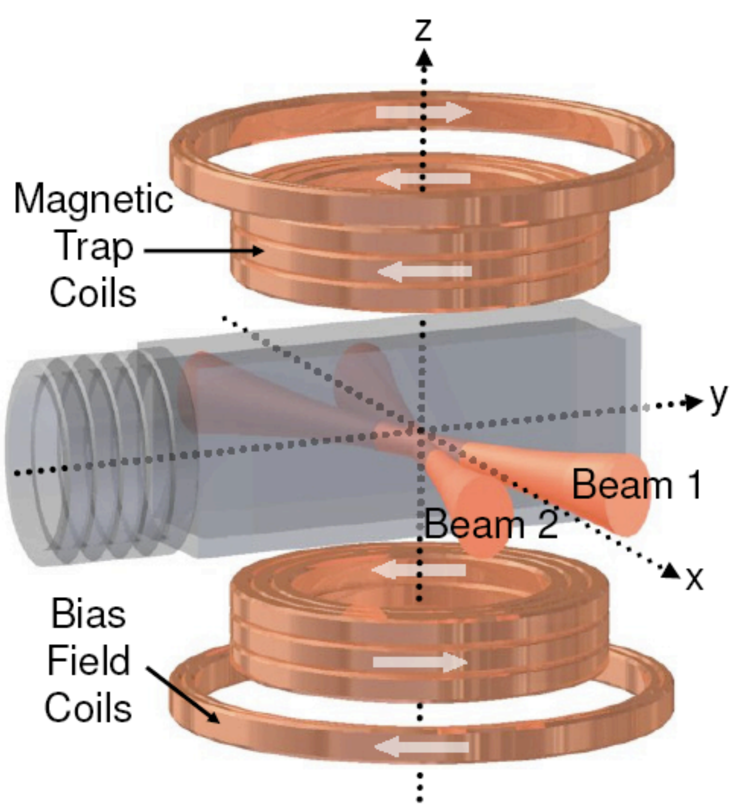

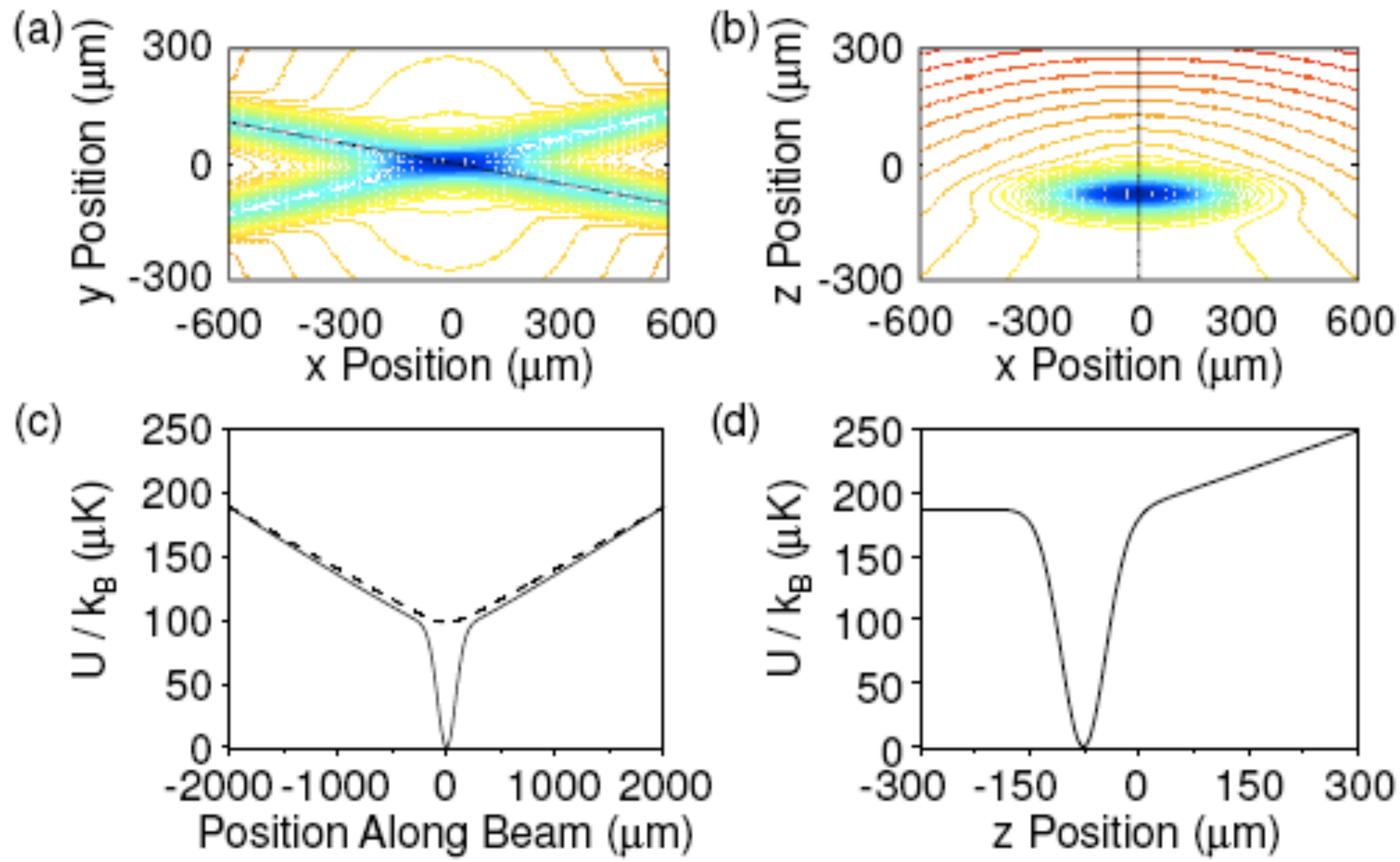

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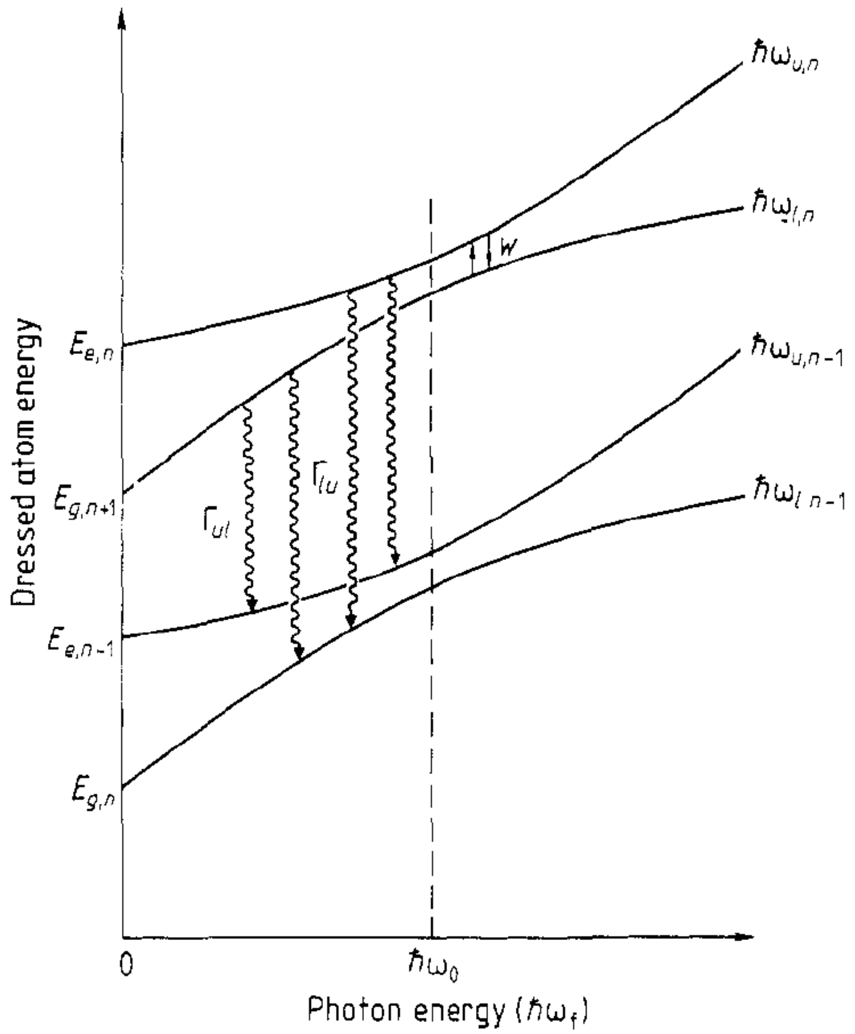
- Atoms are transferred into |1,+1> from |1,-1> by adiabatic rapid passage.
- A 26 x 26 mm square coil of 3 turns are driven to create an RF Filed at 1.5 MHz. A bias field of 22.4 G is then switched on to cross the RF Zeeman resonance at 2.1 G.



$$P_{ad} = 1 - \exp(-\pi\omega_1^2/2|\alpha|)$$

$$\omega_1^2 \gg |\alpha| = (d/dt)|\omega_0 - \omega_f|$$

J. Phys. B: At. Mol. Phys. 17 (1984) 4169-4178

Accepted by Eur. Phys. J. D, (2011)

^{87}Rb BEC in a levitated crossed dipole trap

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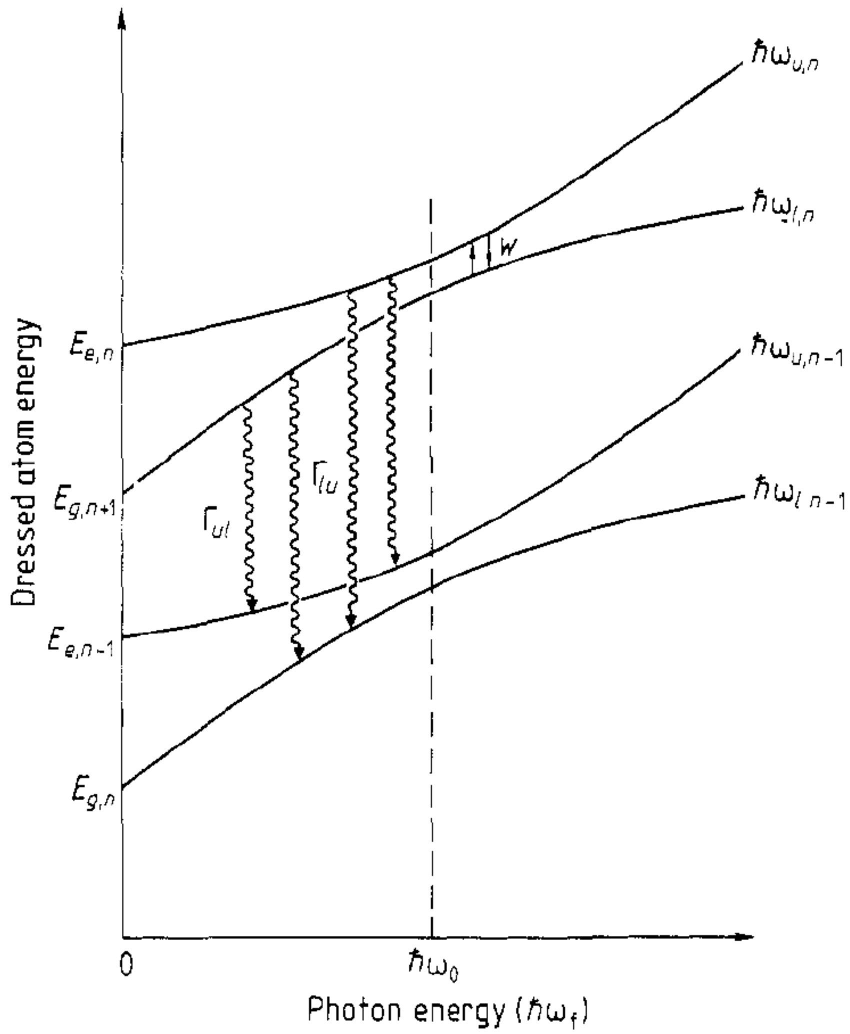

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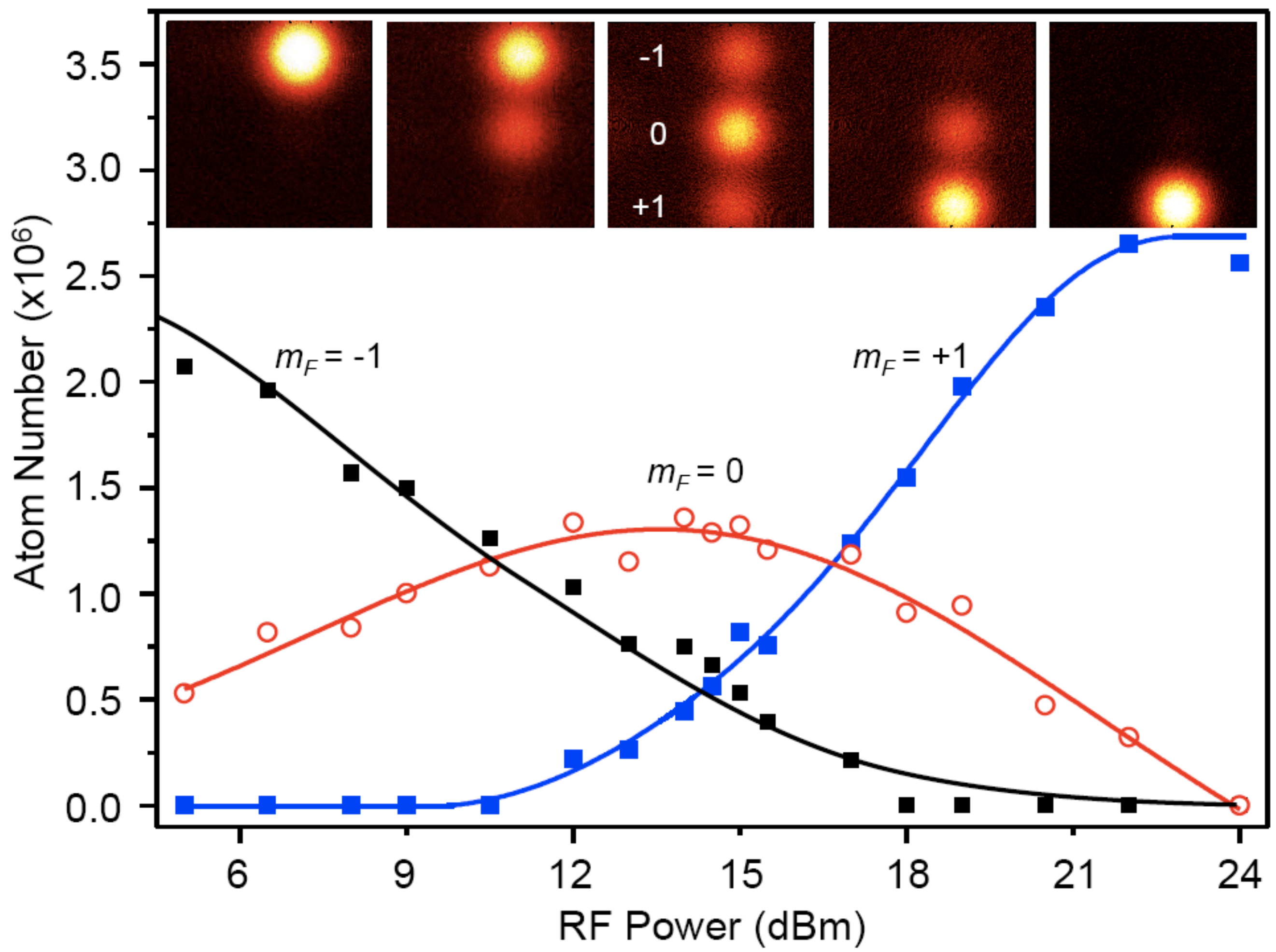

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^{87}Rb BEC in a levitated crossed dipole trap

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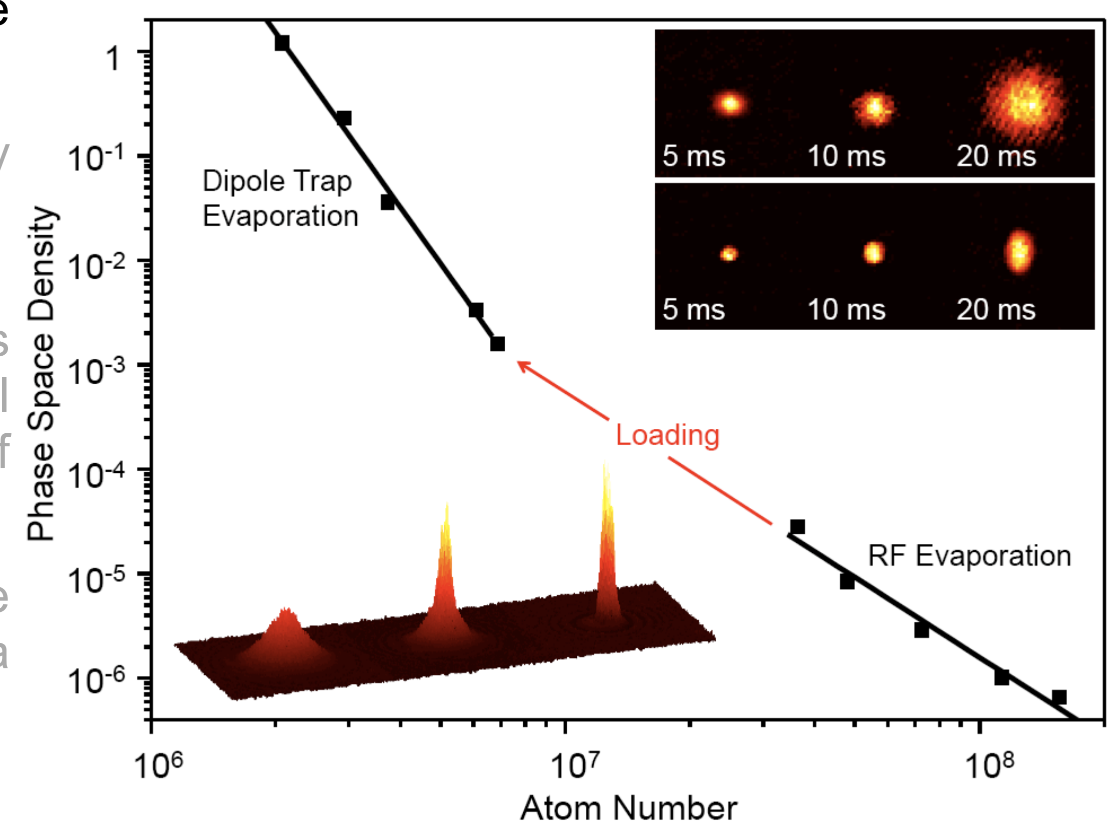
- The phase-space density trajectory to BEC of ^{87}Rb (|1,+1>) in the cross dipole trap. $N_{BEC} = 1 \times 10^6$
- Control the depth of the levitated crossed dipole trap by manipulating the magnetic field gradient.
  C. Chin, Phys. Rev. A, 78, 011604(R), 2008
- Sympathetic cooling of different spin states in the levitated cross dipole trap by a tilting potential. The inset shows the vertical cross-section through the potential minimum for a beam power of 0.45 W and a magnetic field gradient of 13 G/cm.
- Application of the experiment to sympathetic cooling of ^{133}Cs. The dipole trap potential corresponds to 100 mW in each beam, a magnetic field gradient of 38 G/cm and a bias field of 22.4 G.



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^{87}Rb BEC in a levitated crossed dipole trap

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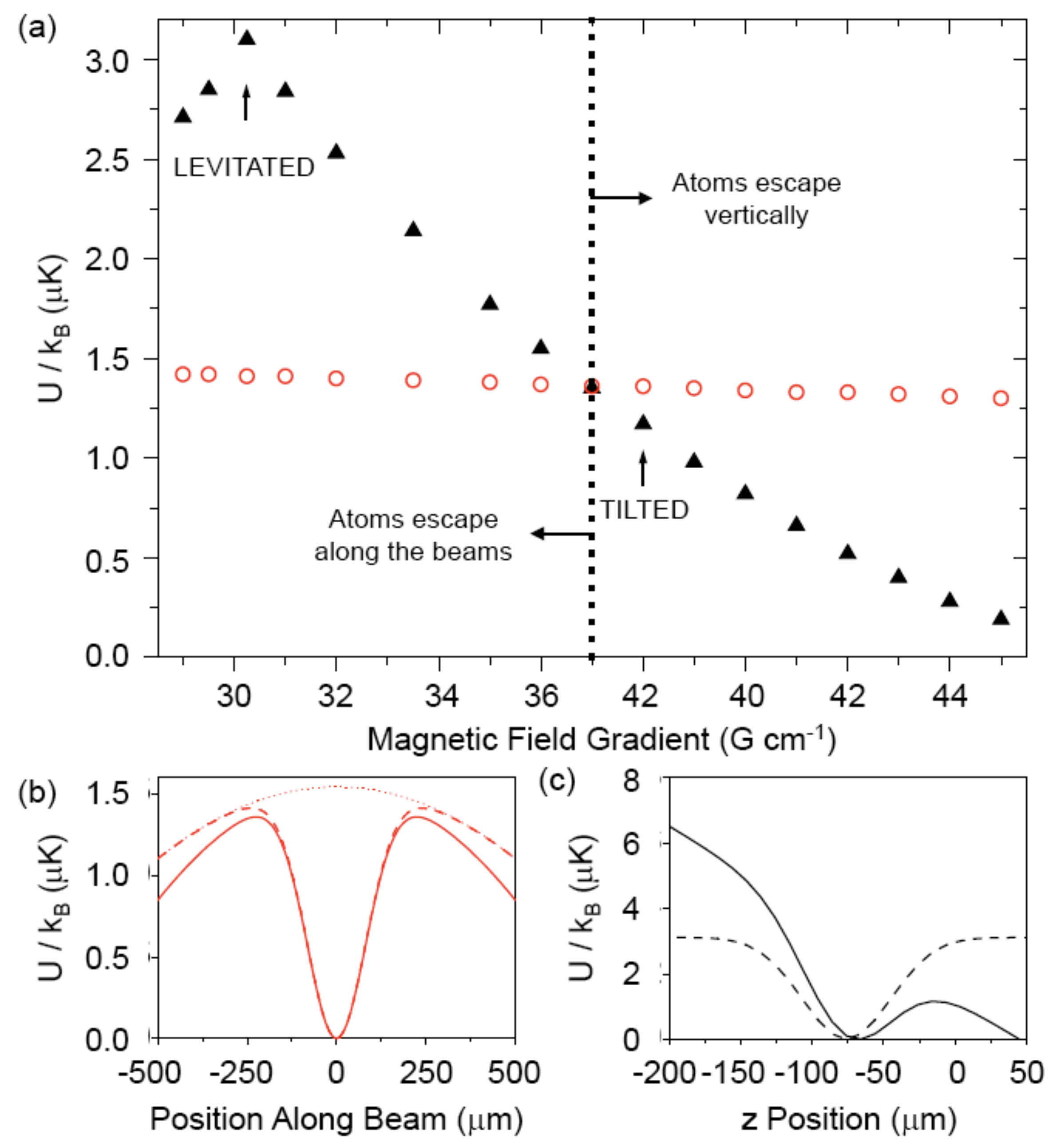

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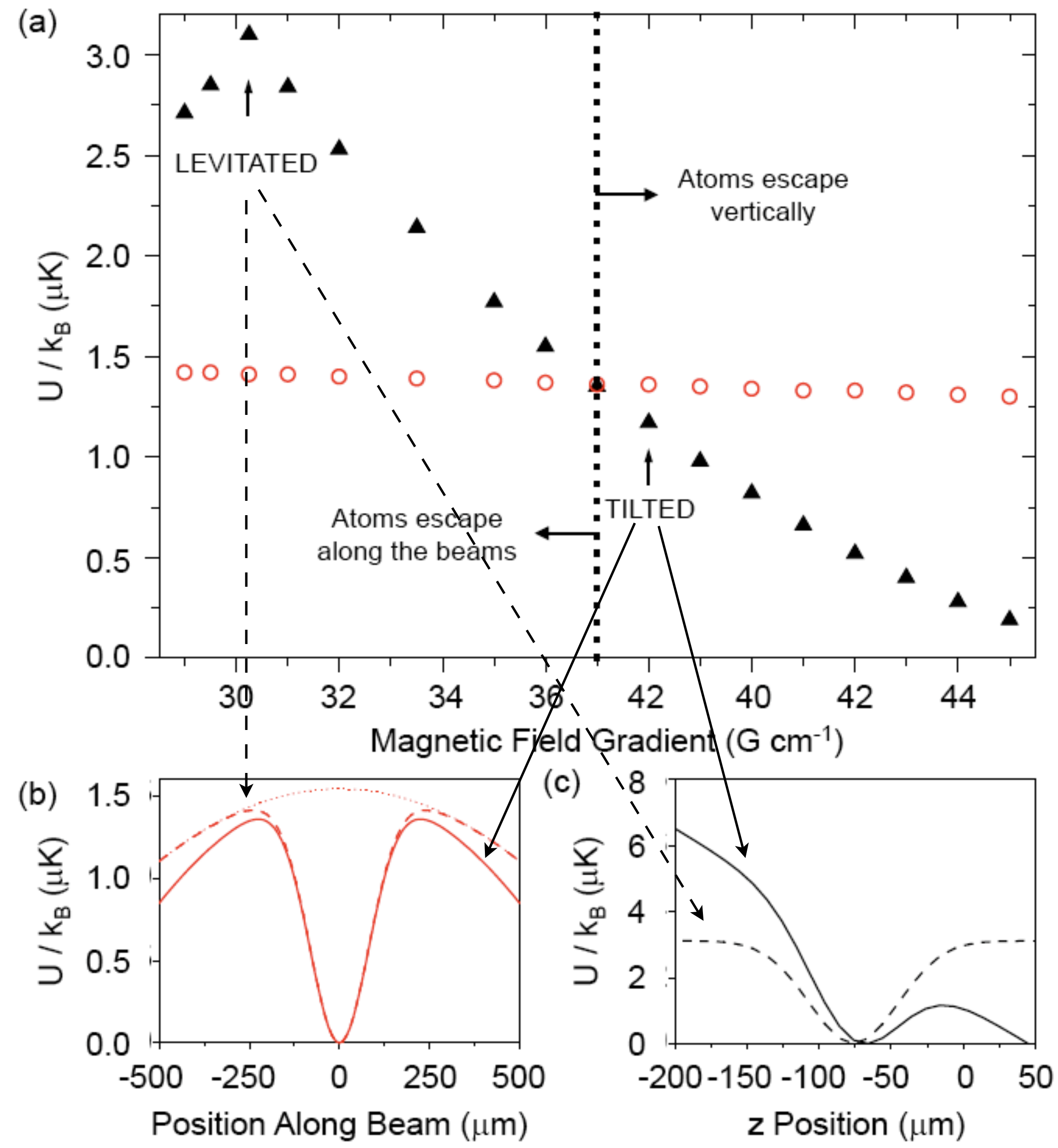

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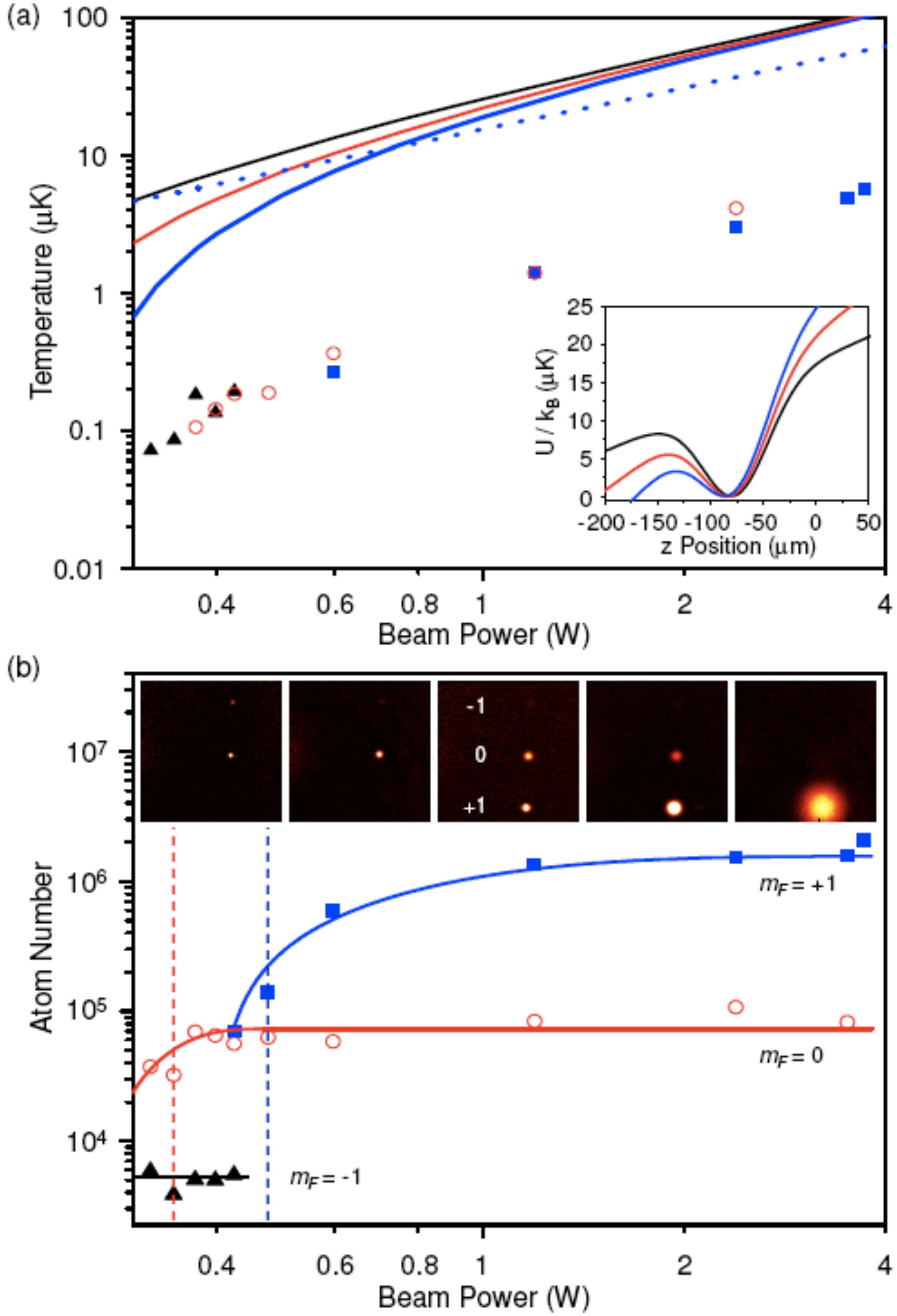

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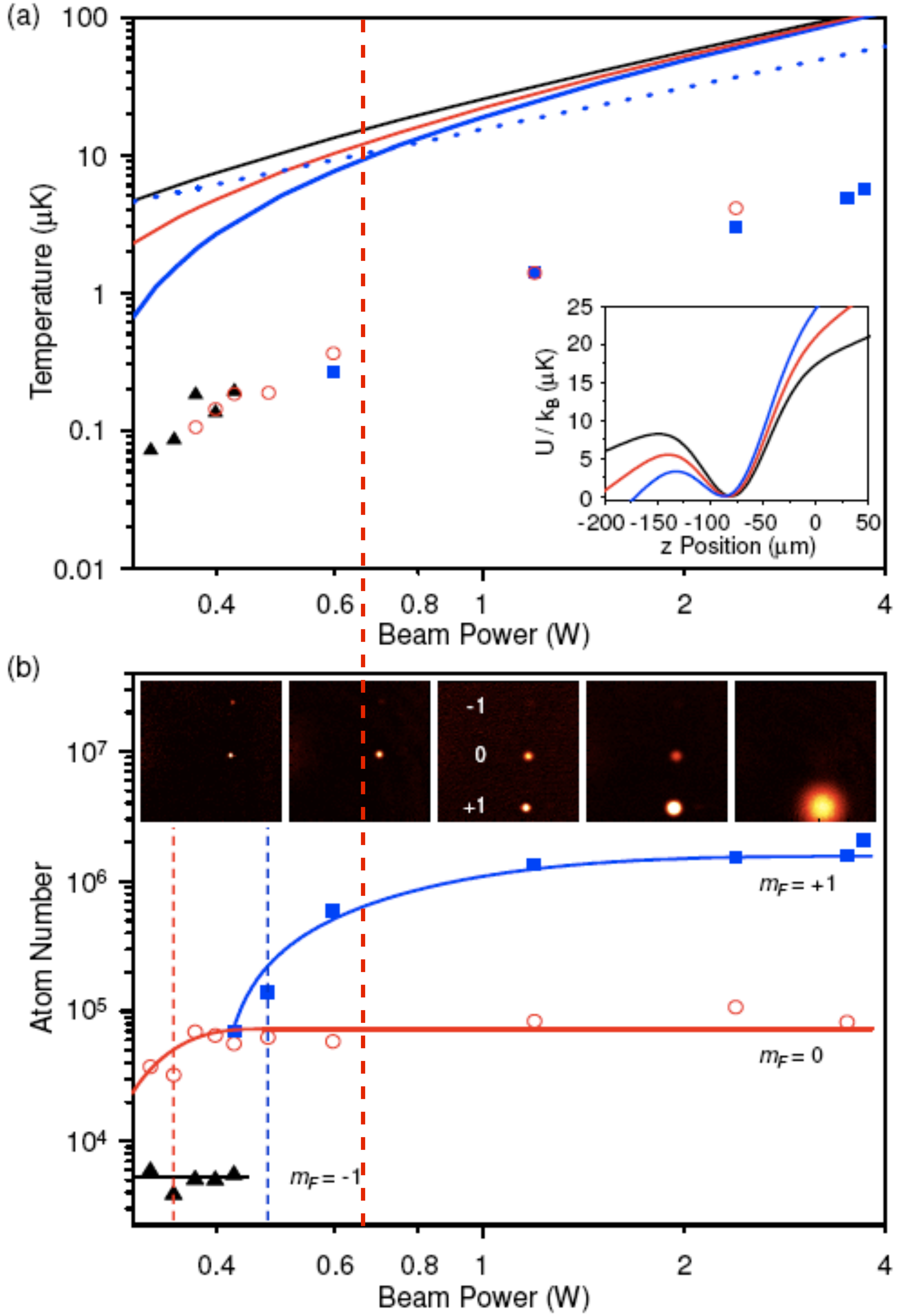

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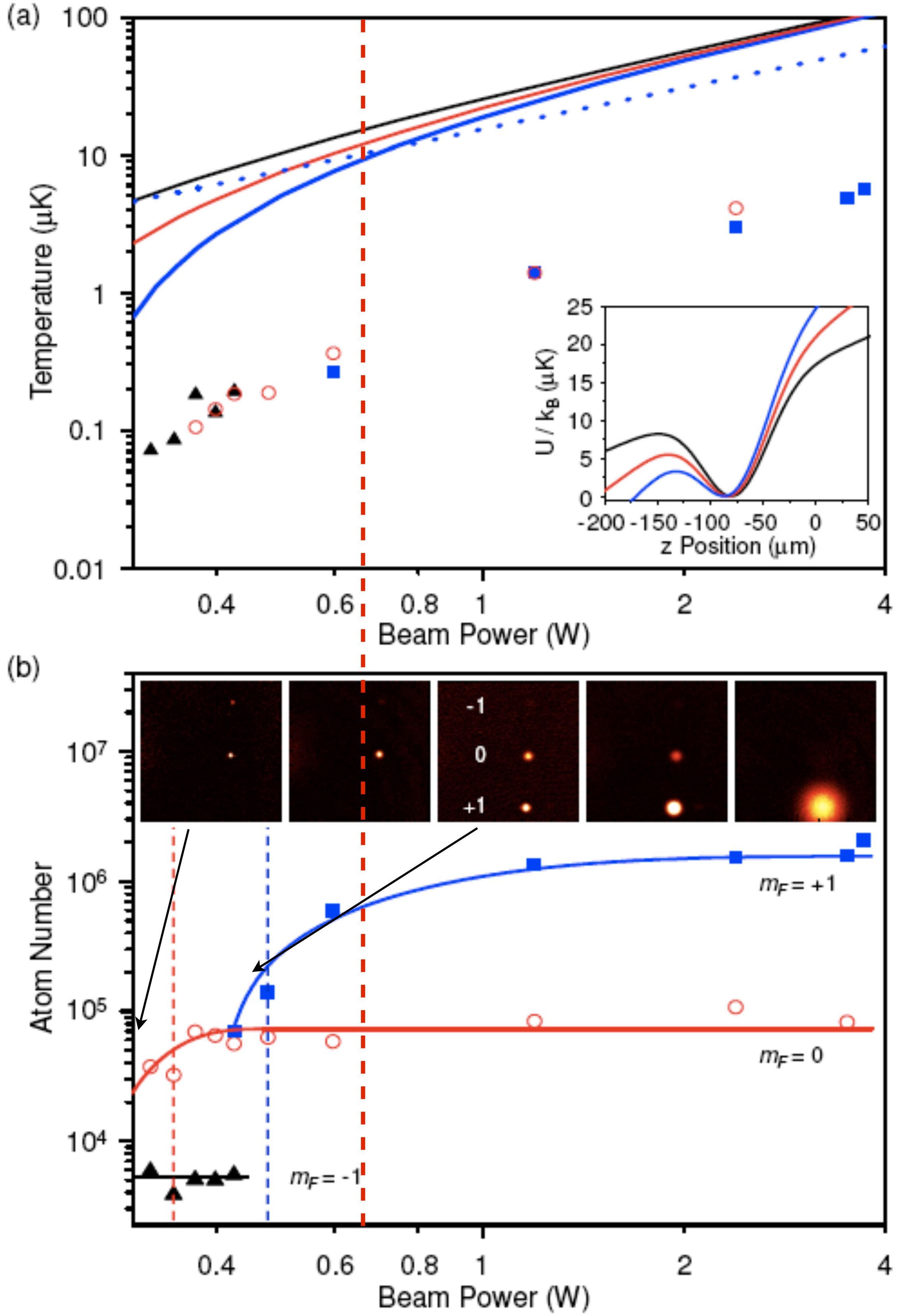

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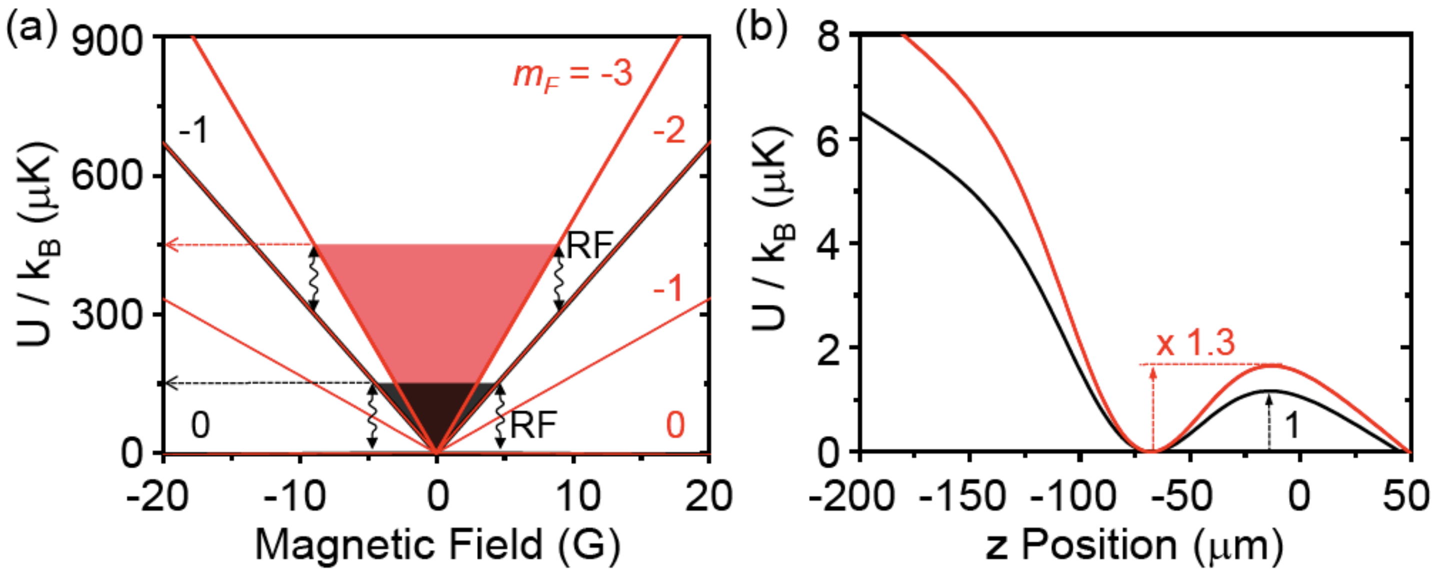

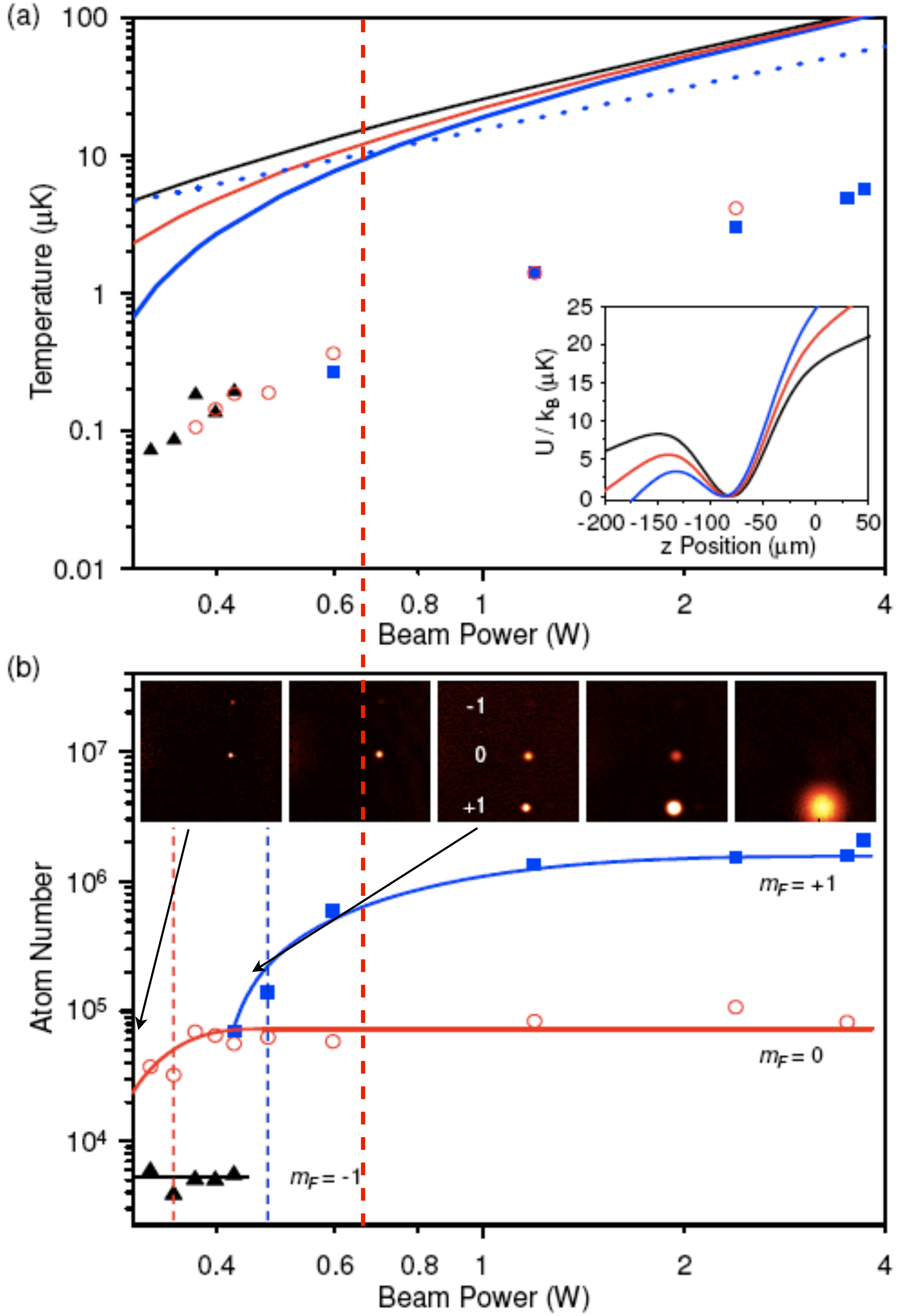

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^{133}Cs BEC in the cross-dipole trap

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Why ^{87}Rb?

Why ^{133}Cs?

^{133}Cs BEC in the cross-dipole trap

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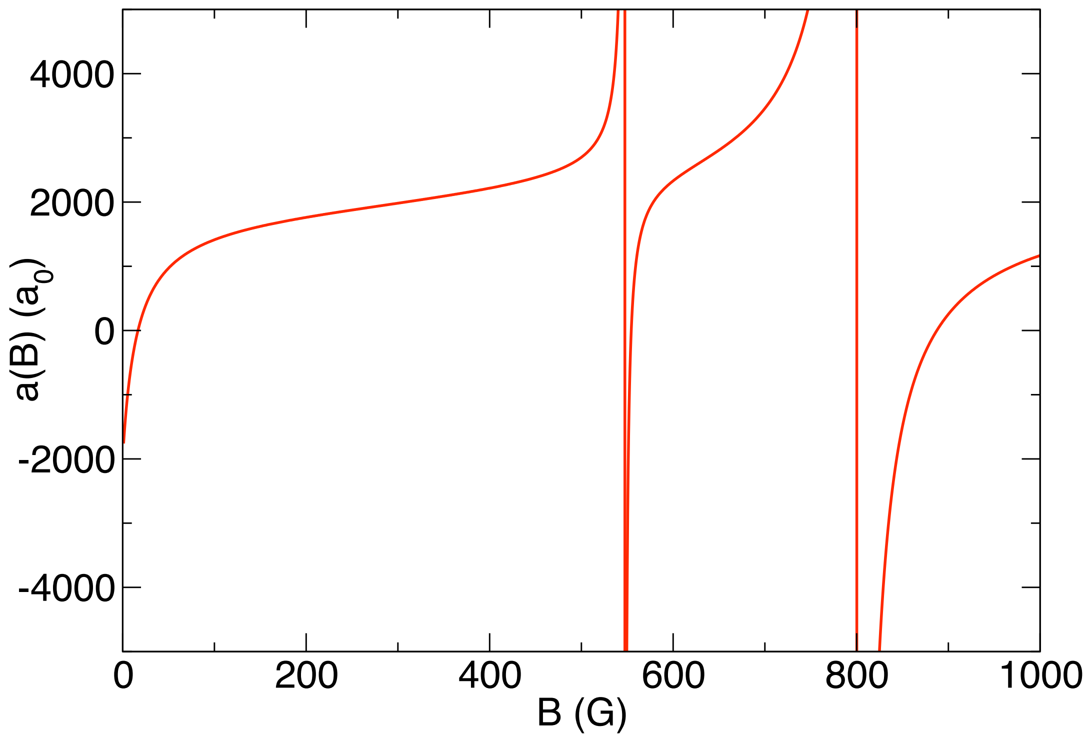

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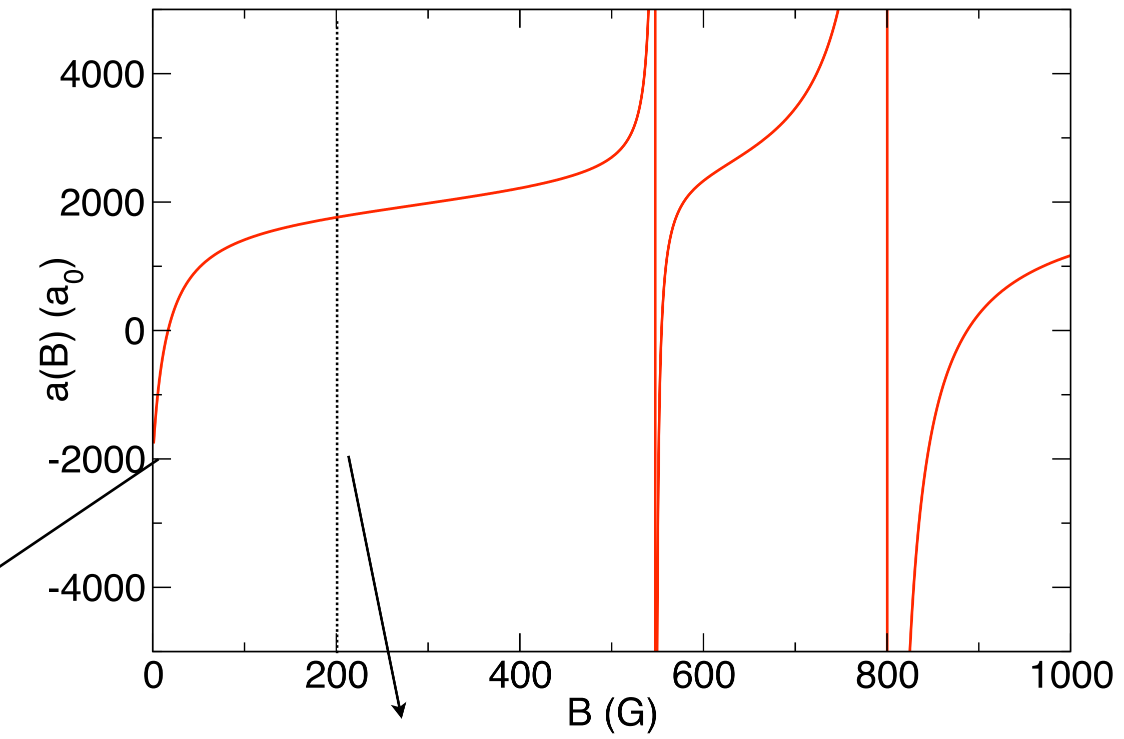

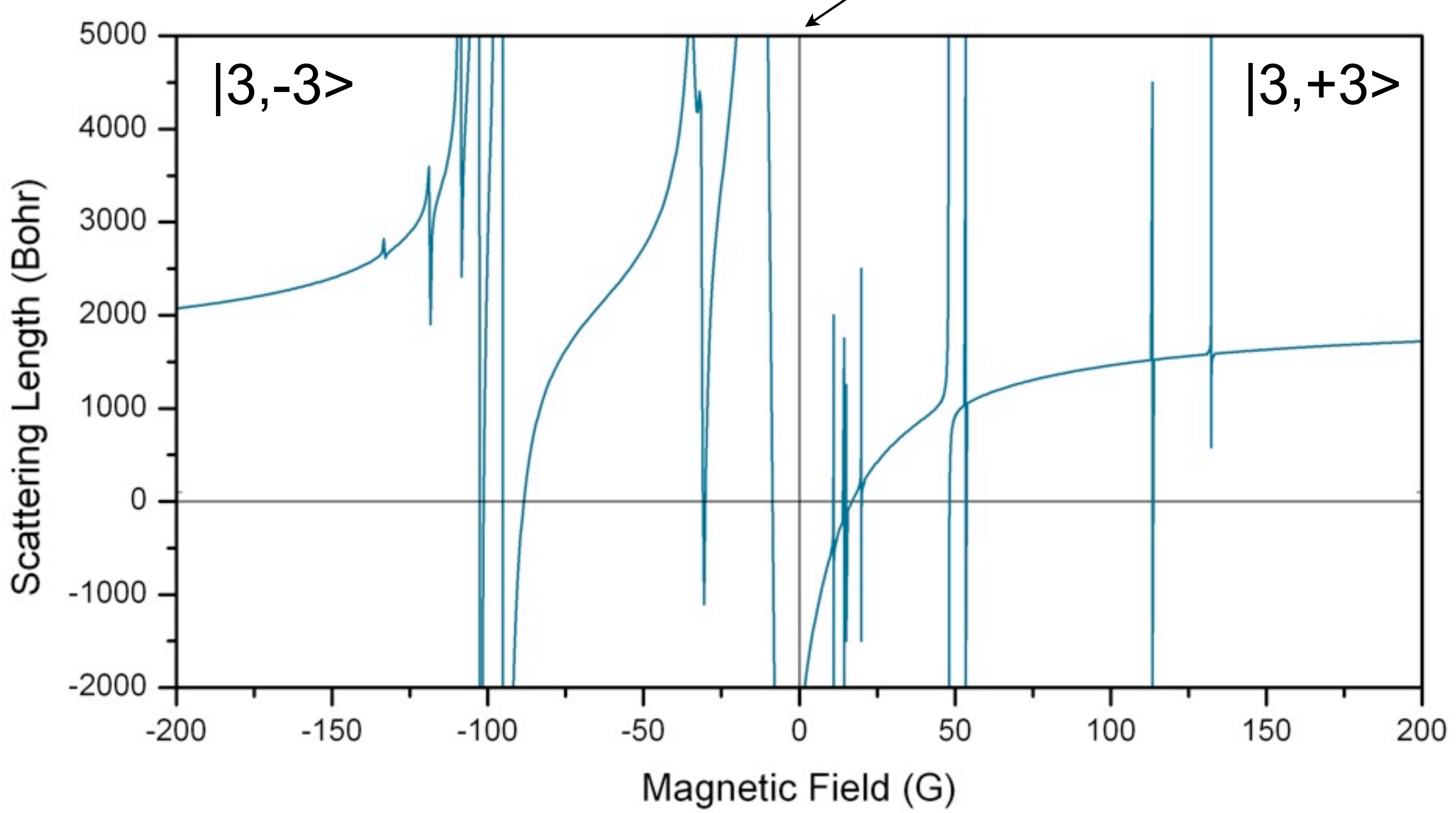

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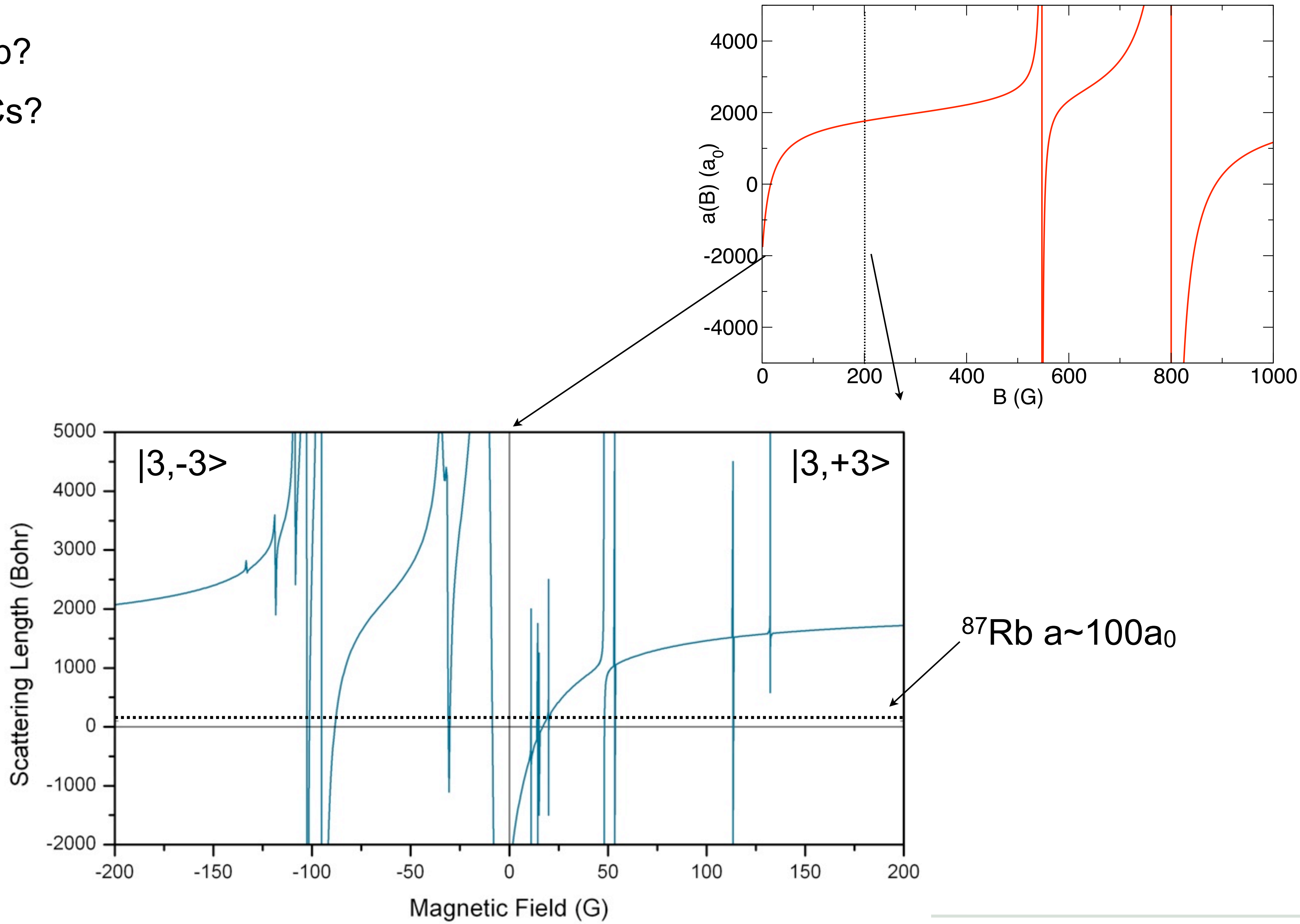

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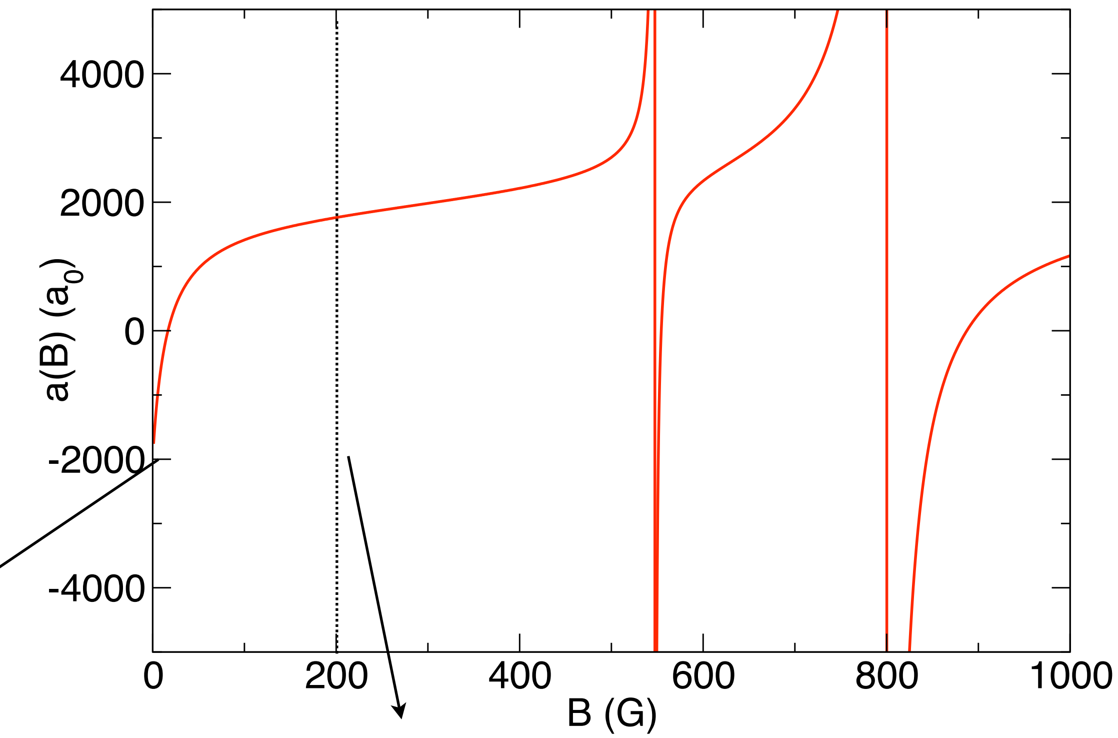

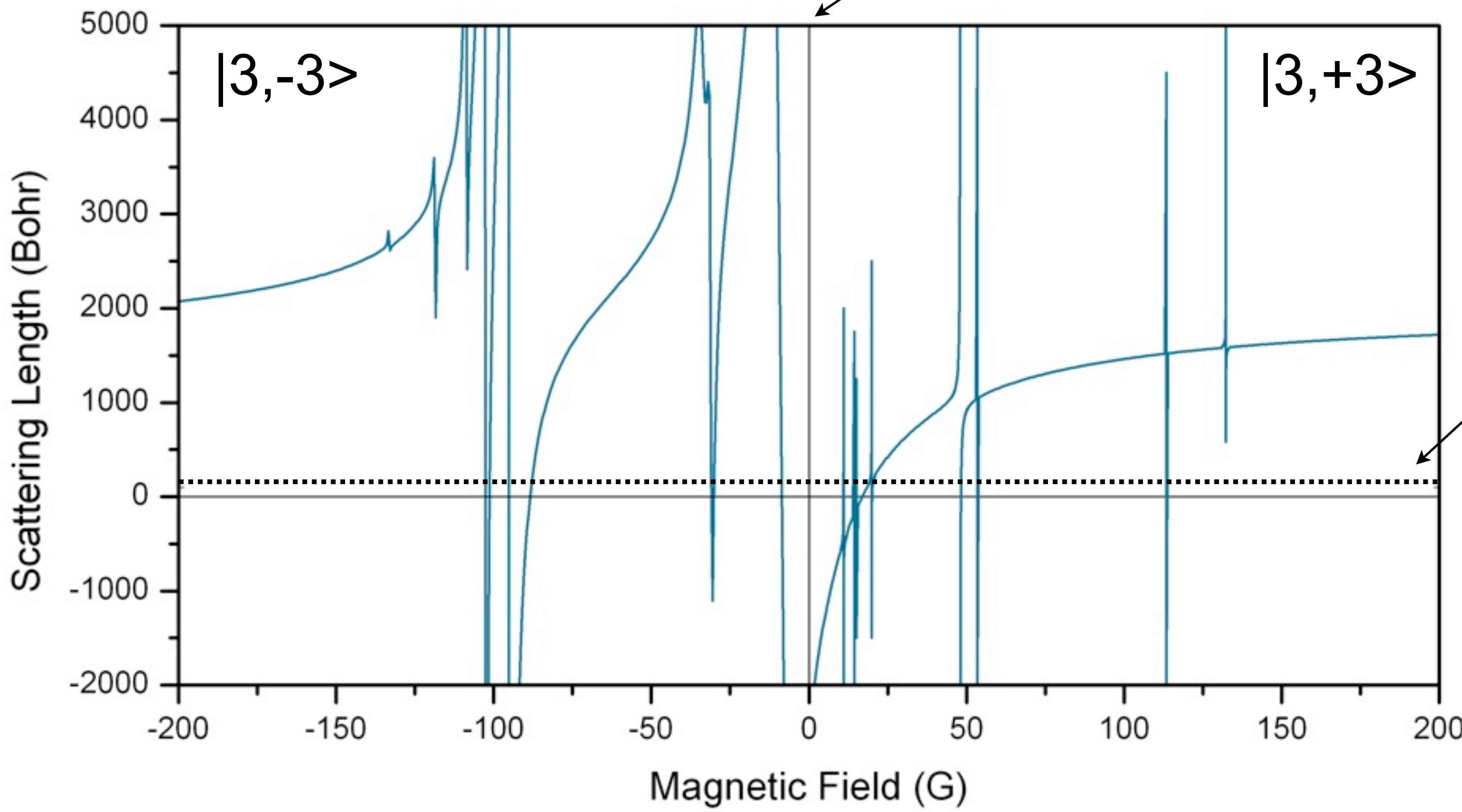

^{87}Rb a~100a_0

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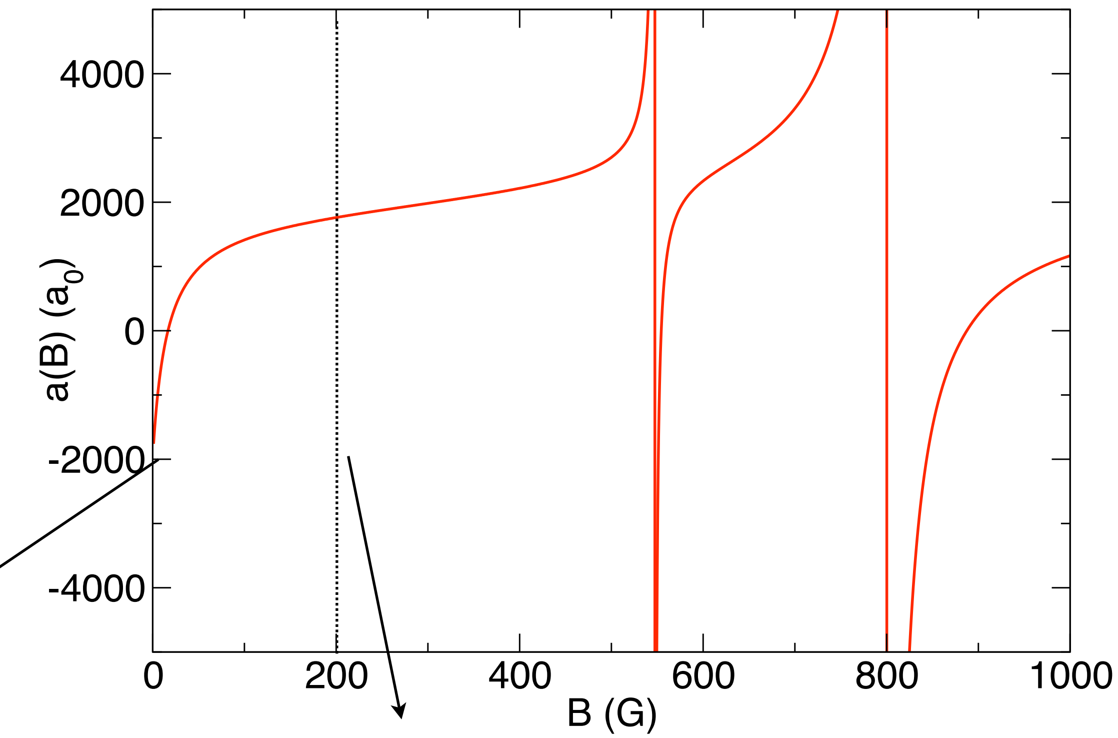
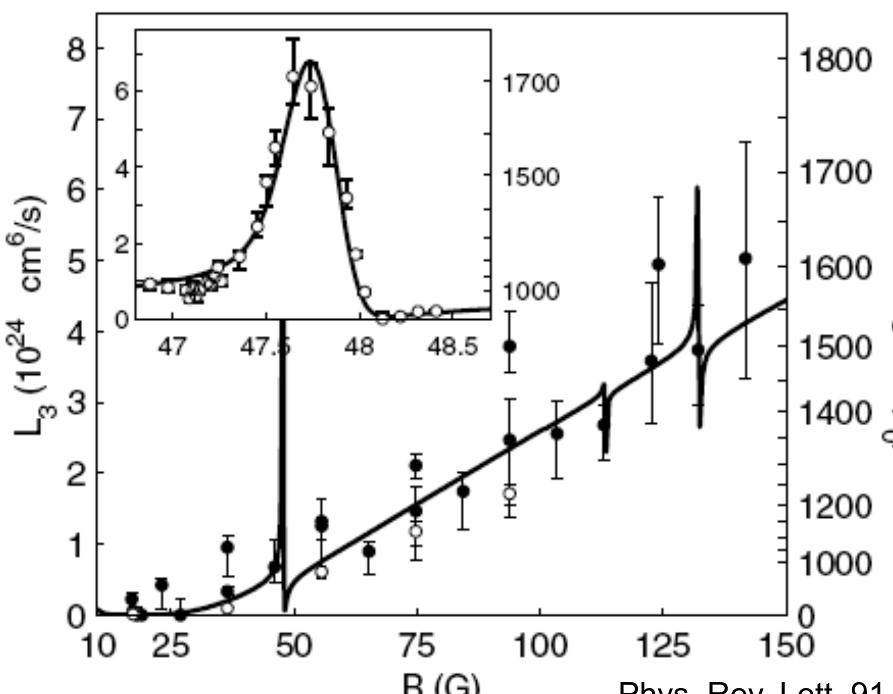
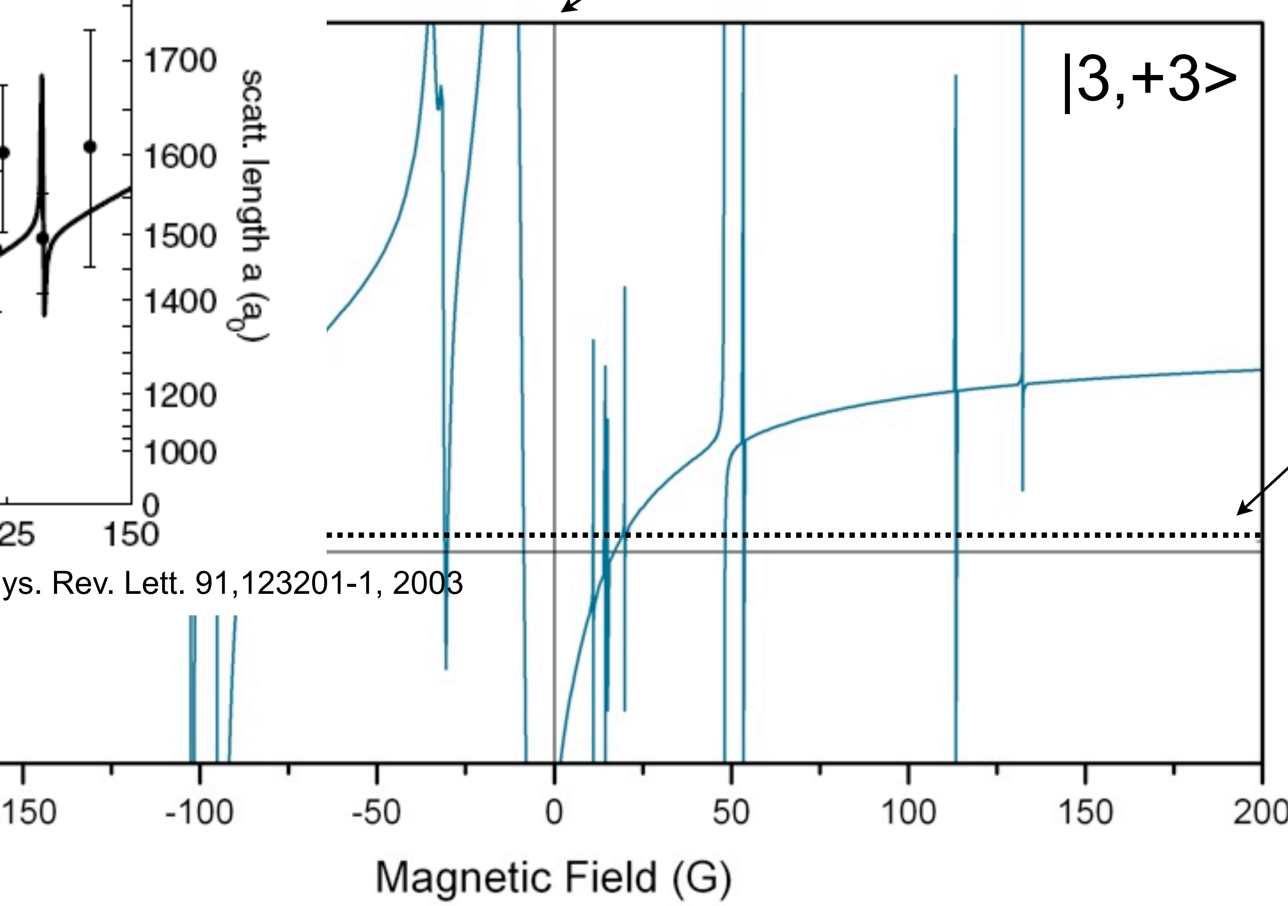




Phys. Rev. Lett. 91,123201-1, 2003



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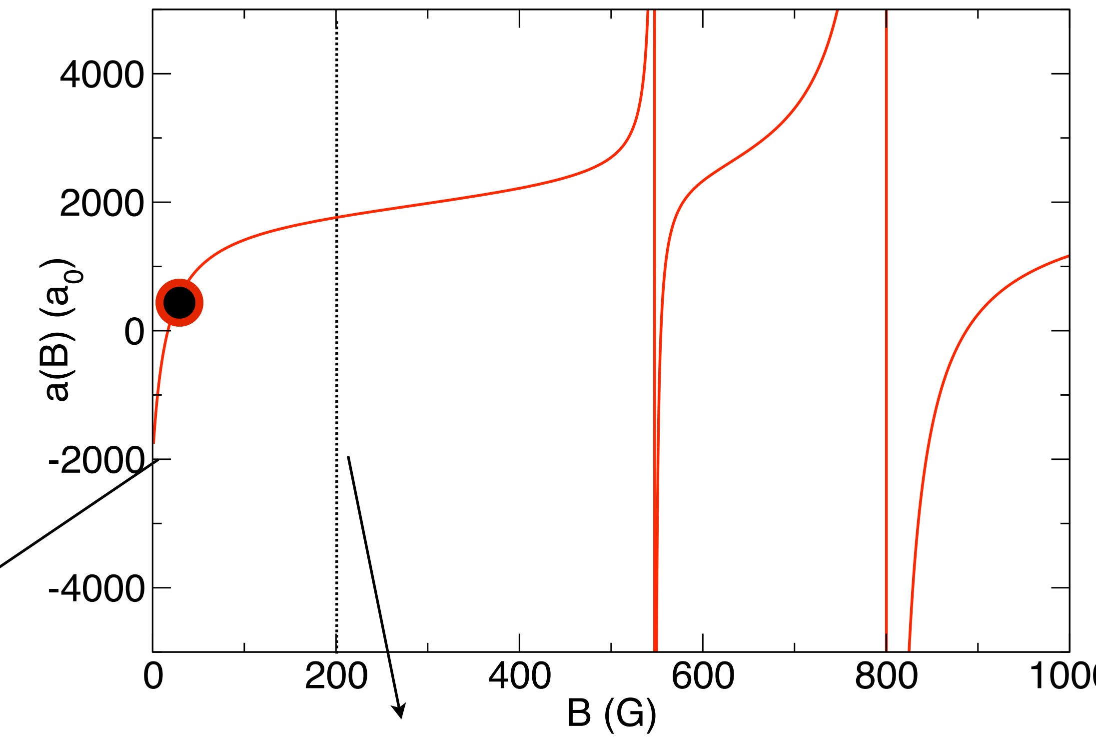

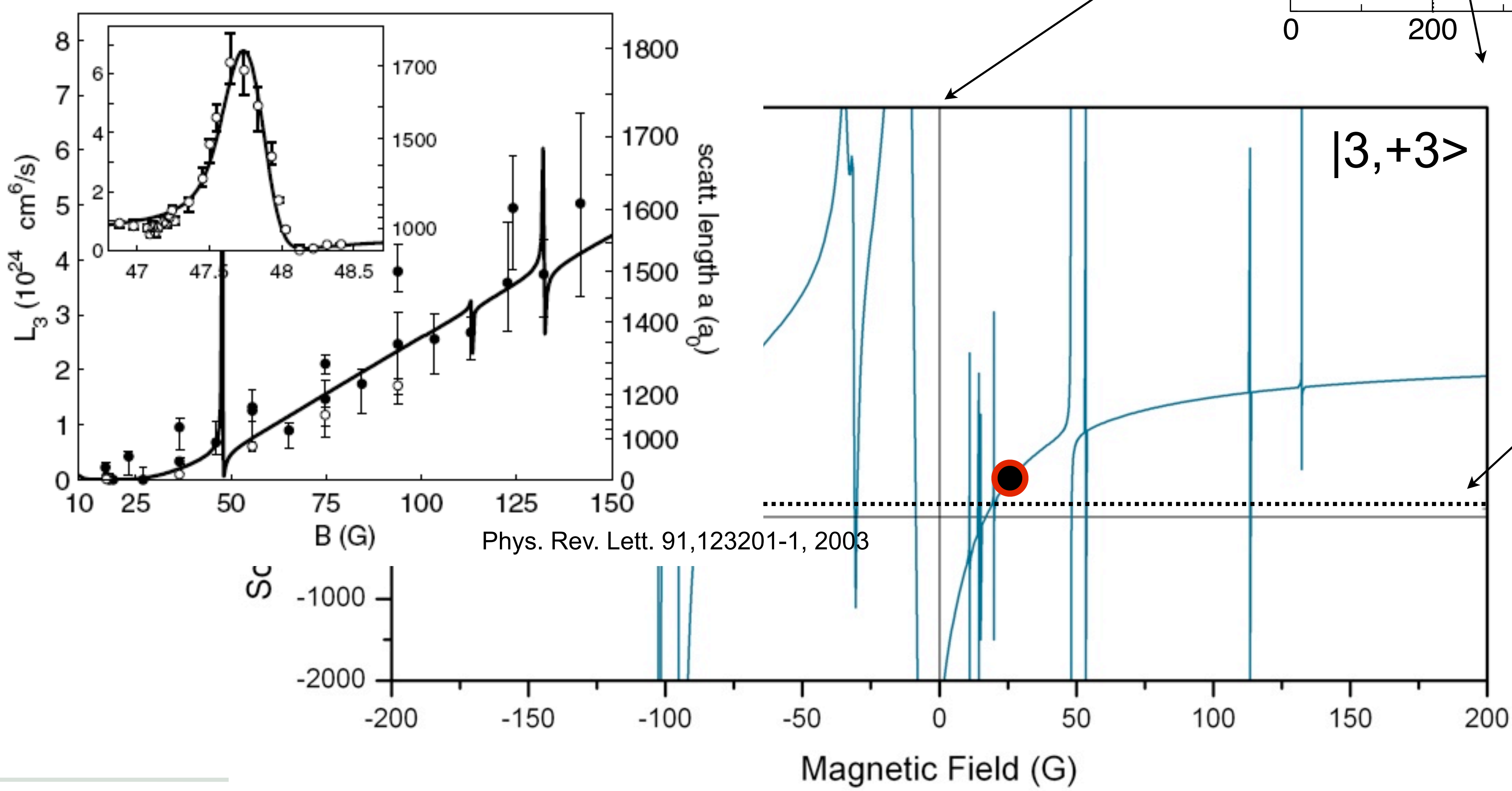

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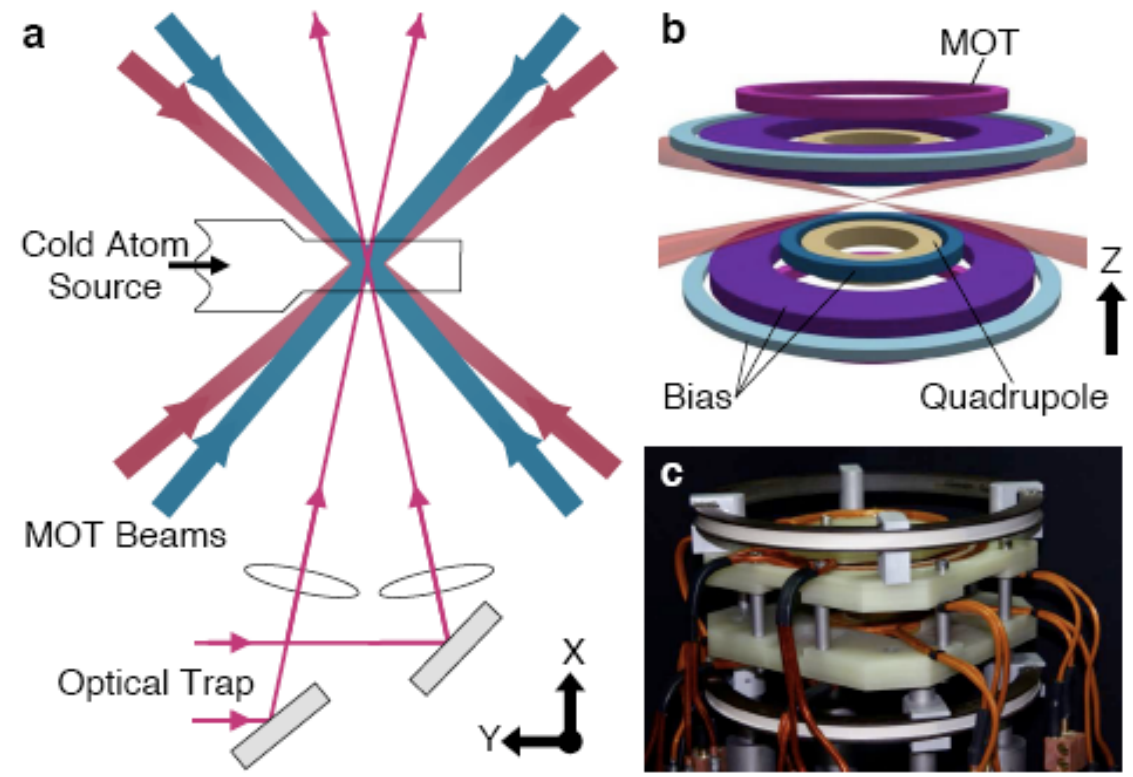

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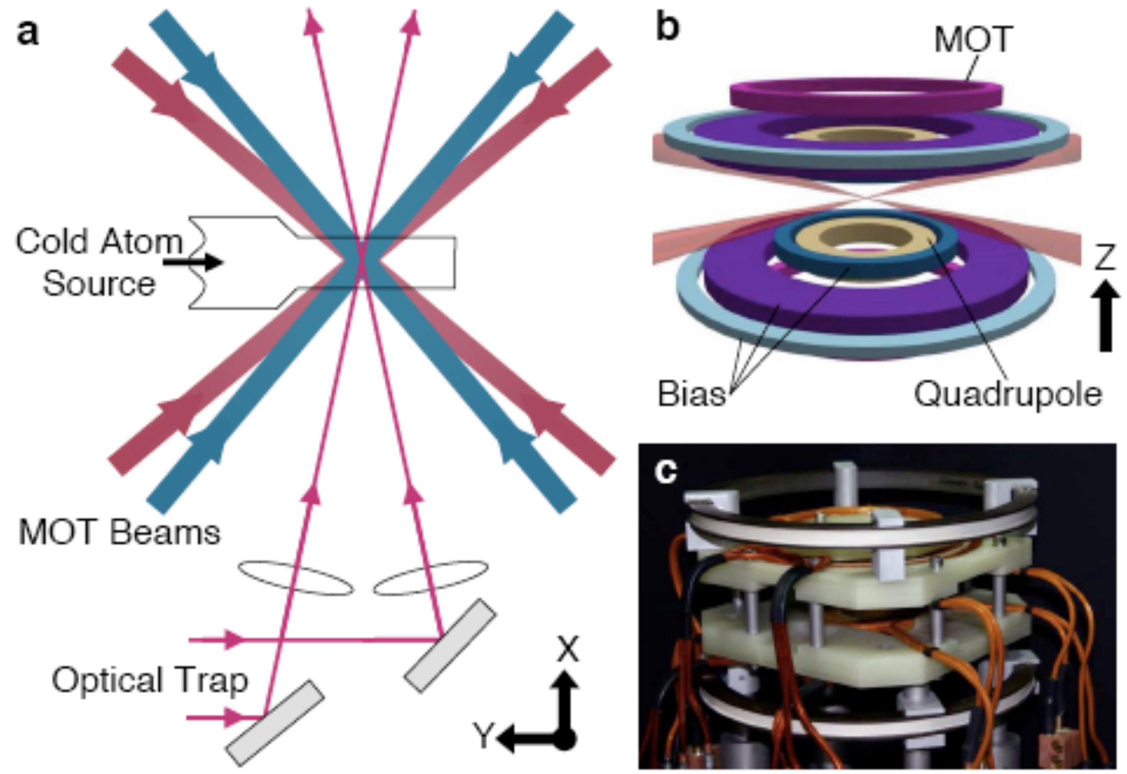

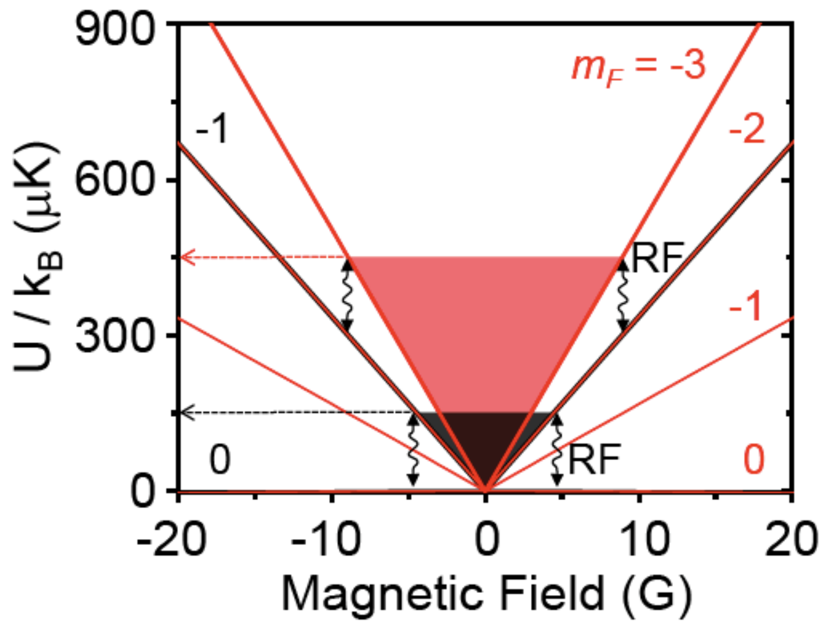

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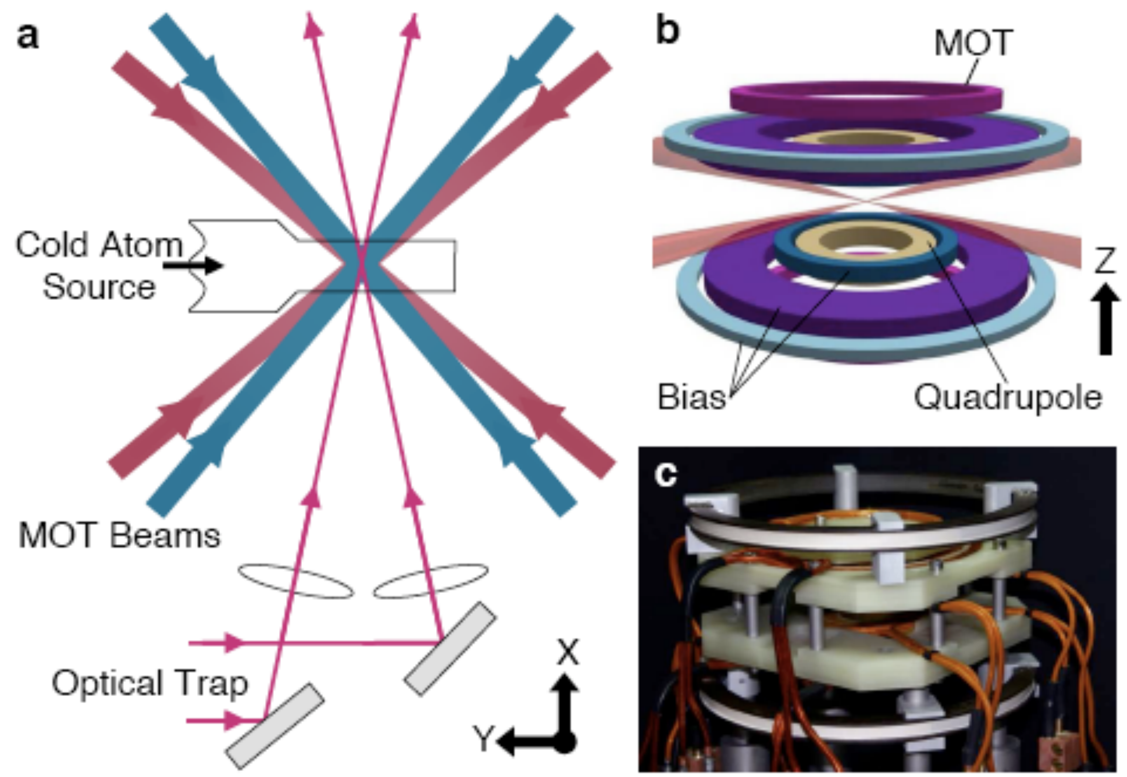

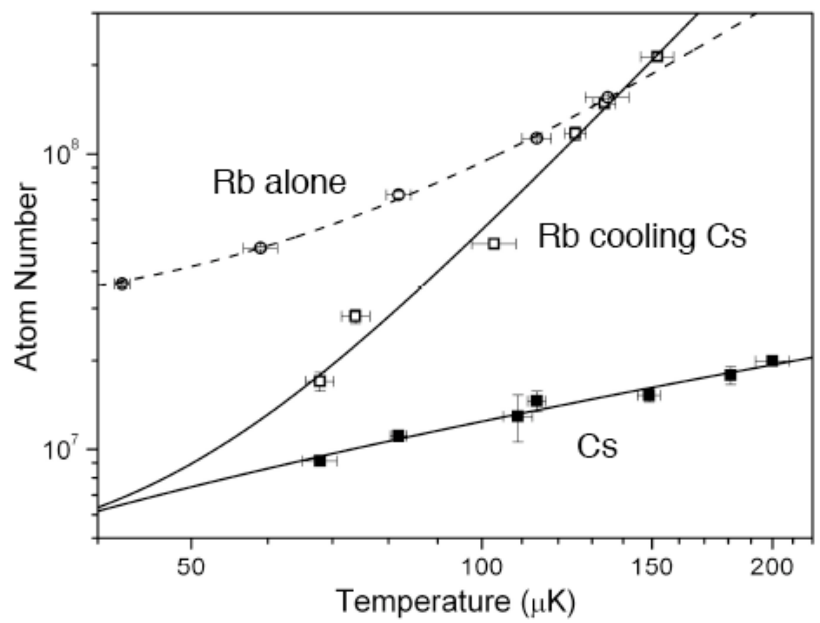

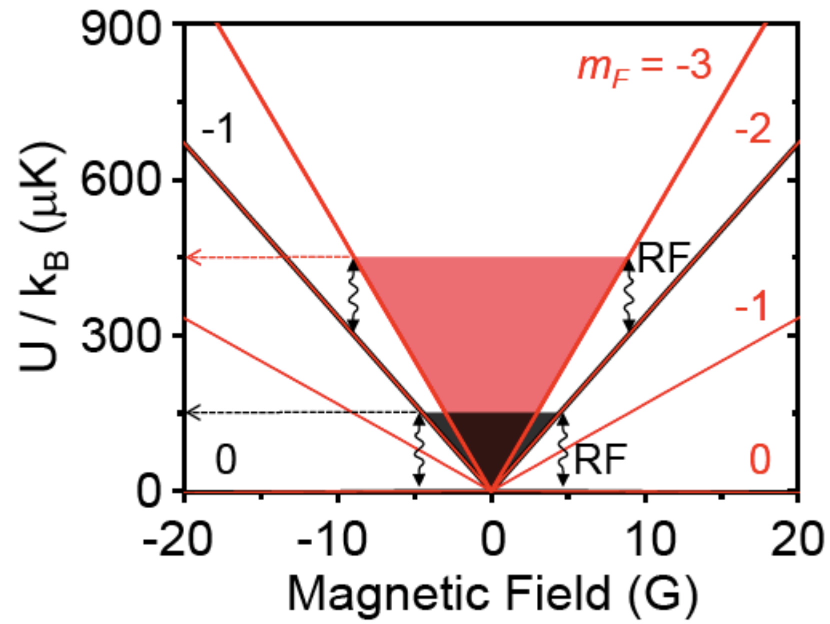

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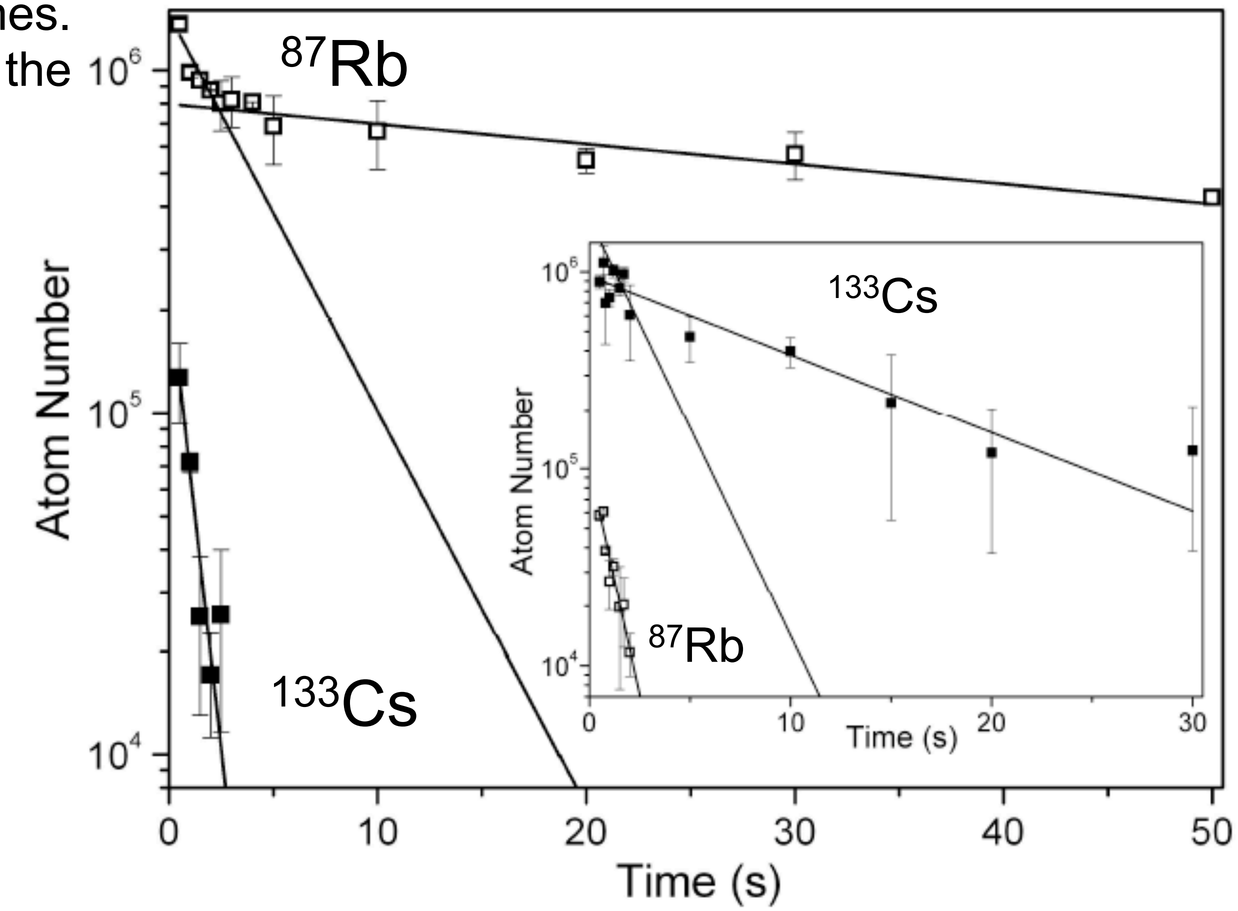
-τ_{Cs}= 0.8(1) s, τ_{Rb}= 4(1) & 70(10) s.
-τ_{Rb}= 0.9(2) s, τ_{Cs}= 2(1) & 10(3) s.



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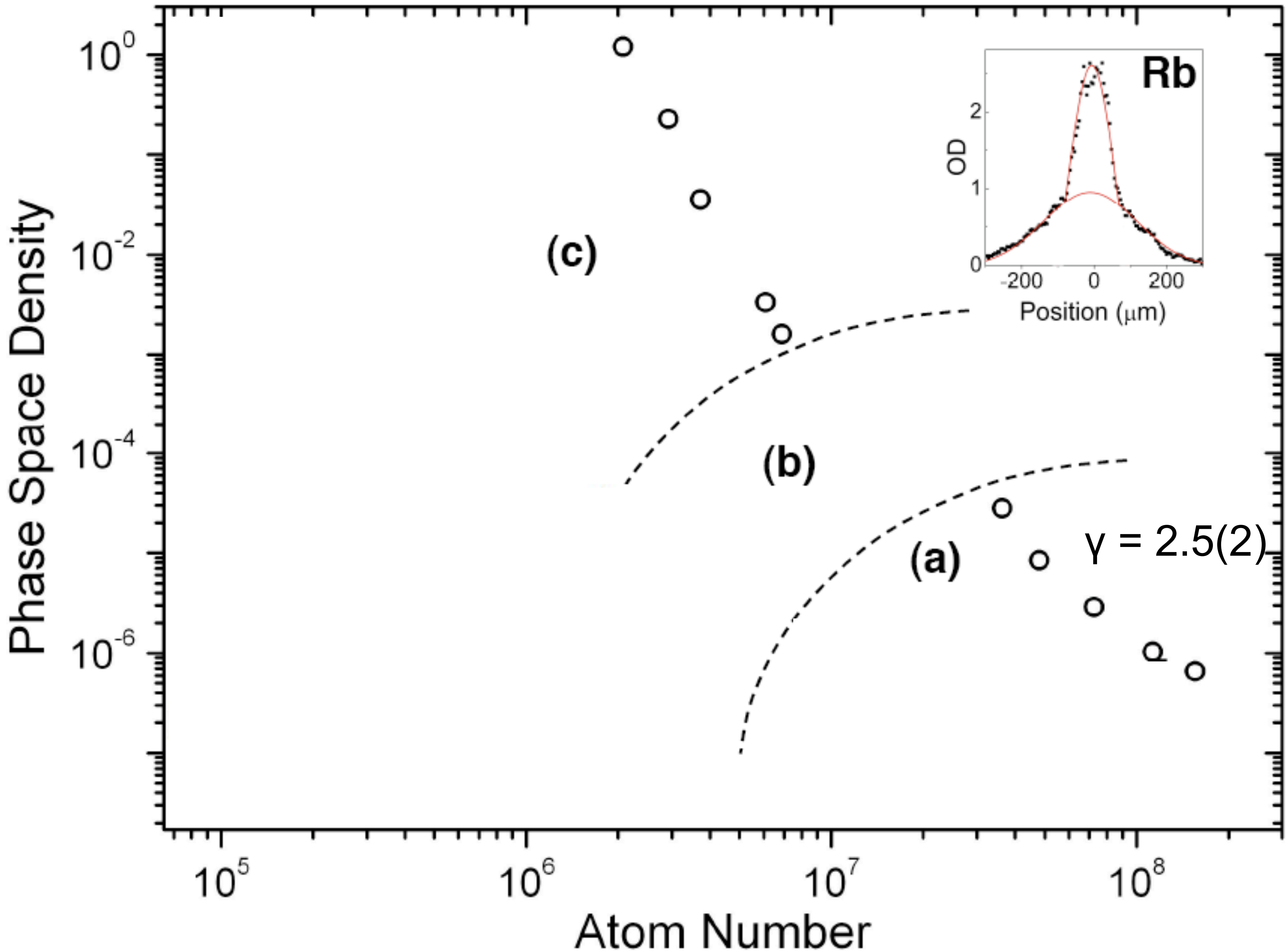

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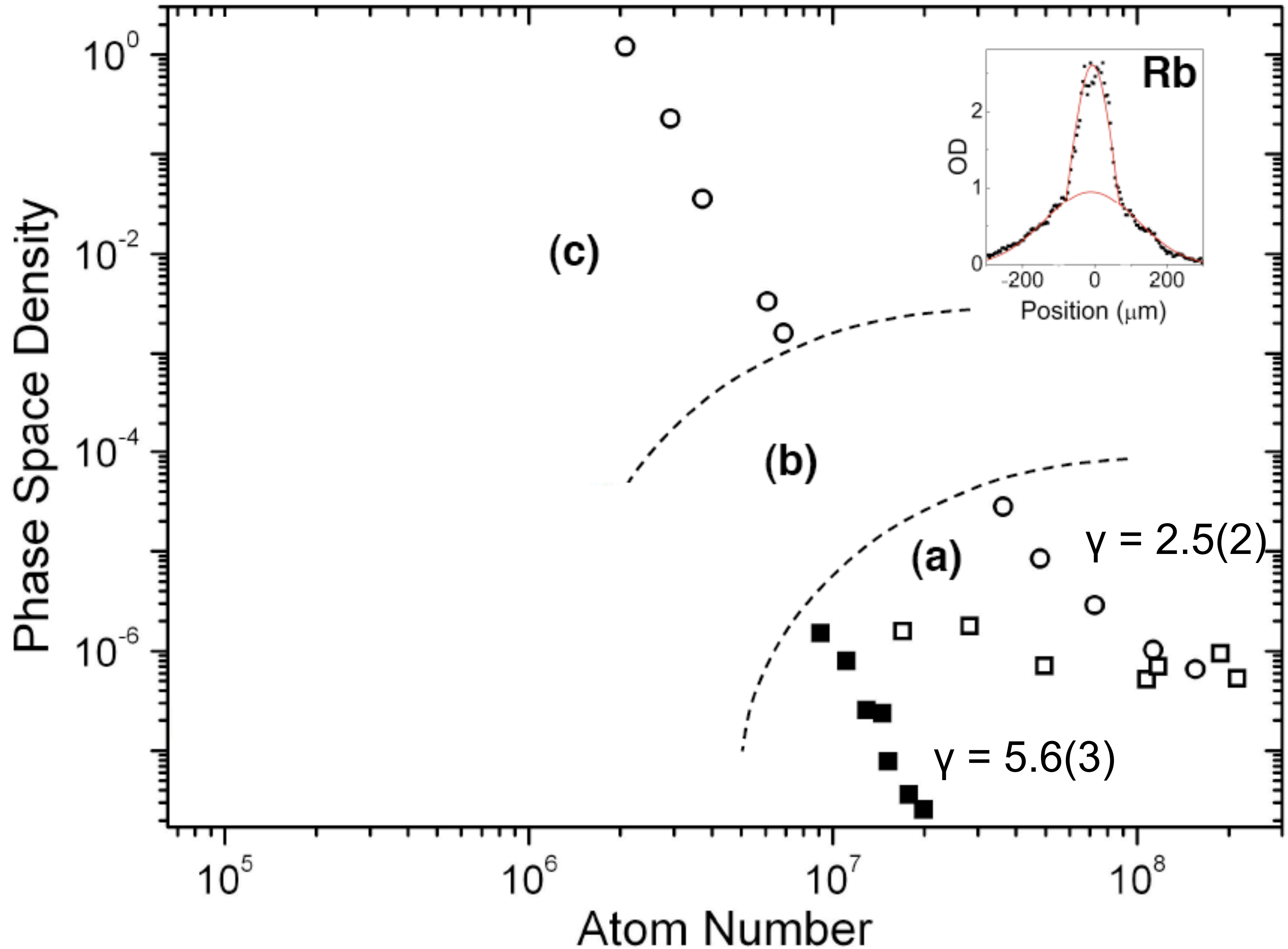

arXiv:1102.1576

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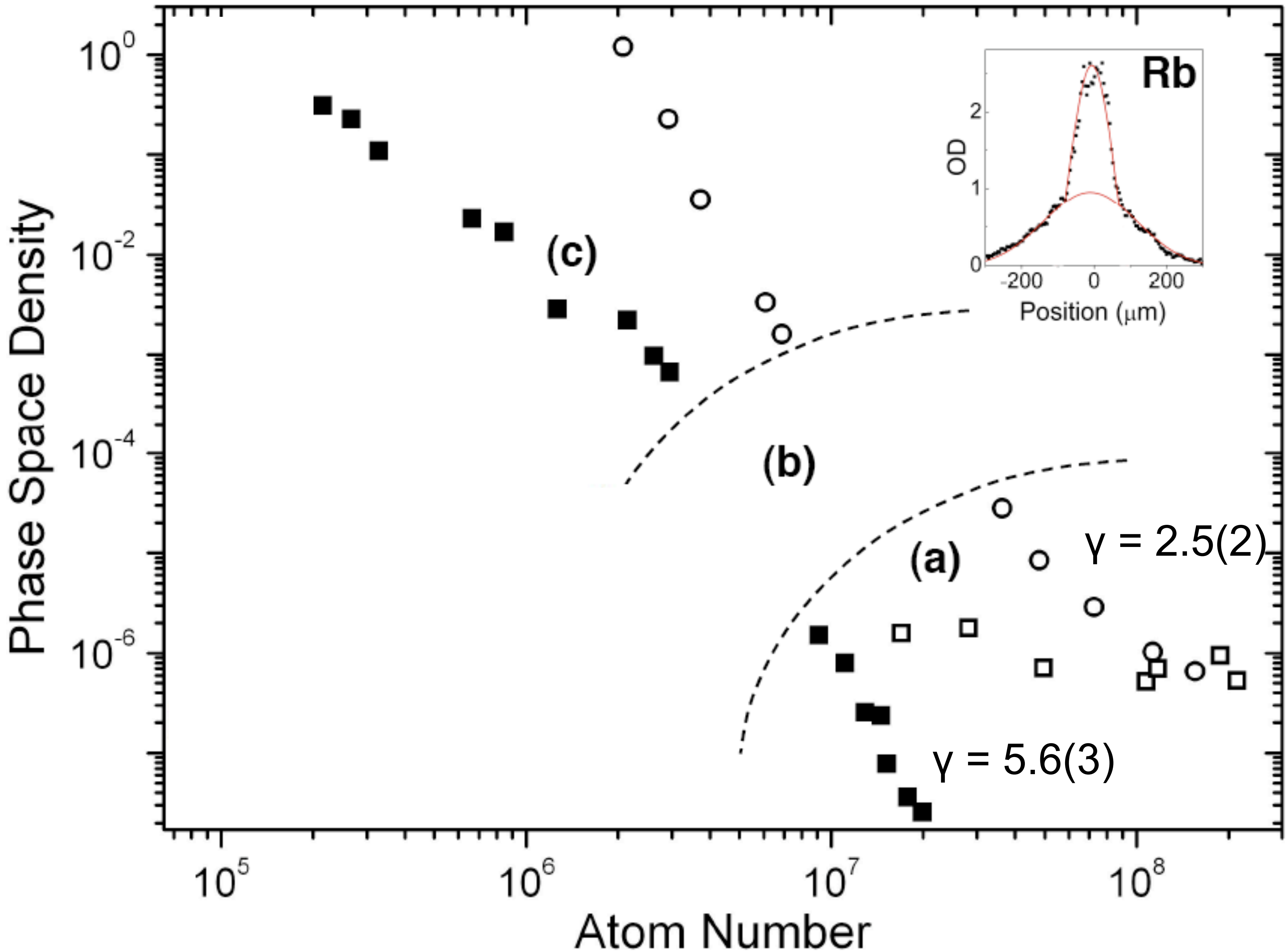
To avoid the interspecies loss and optimise the transfer of ^{133}Cs, RF frequency is reduced to remove all ^{87}Rb. The resulting loading is highly efficient with ~50% of ^{133}Cs transferred into dipole trap. This is double the atoms number loaded compared to ^{87}Rb absence case.



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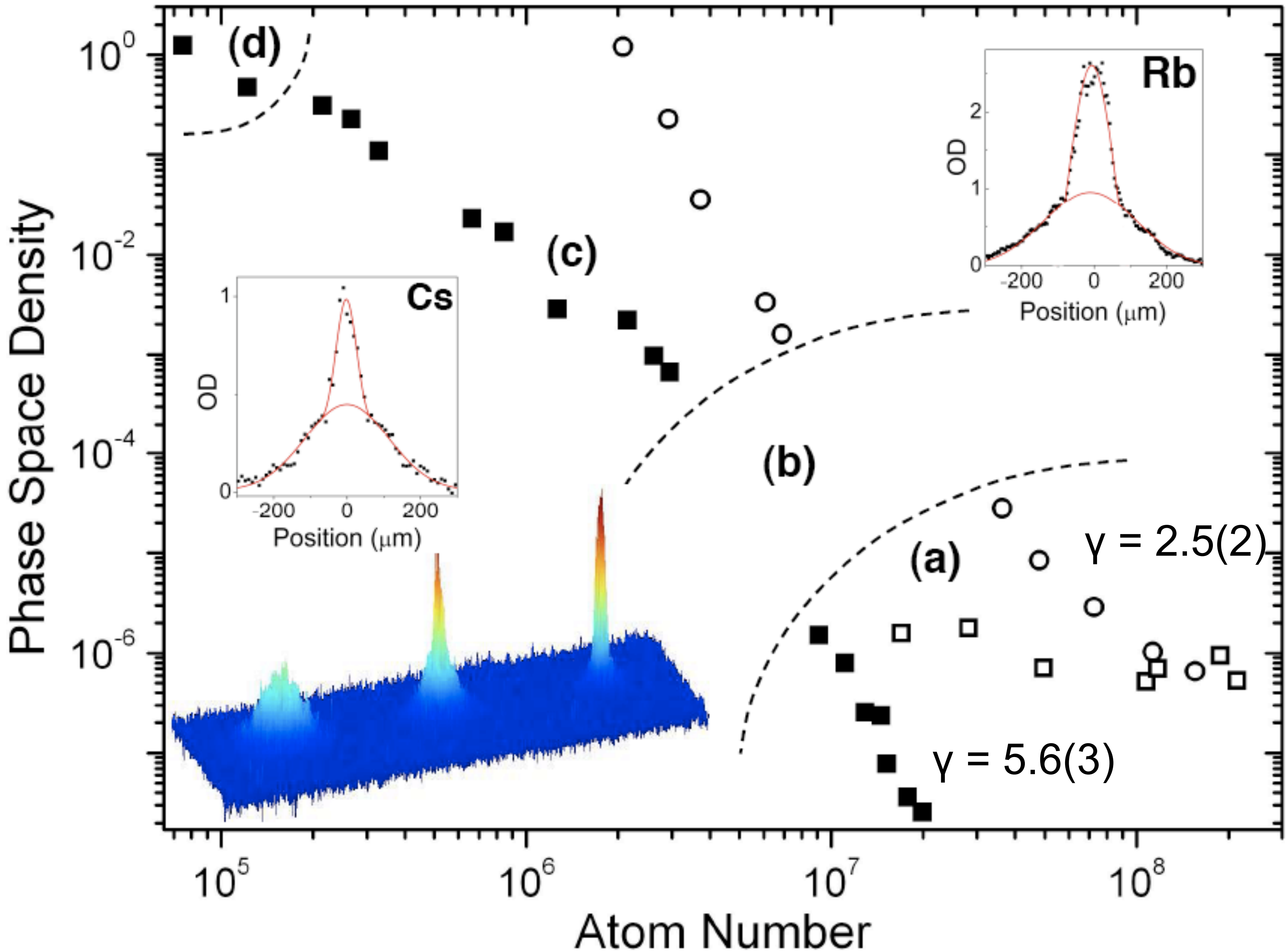

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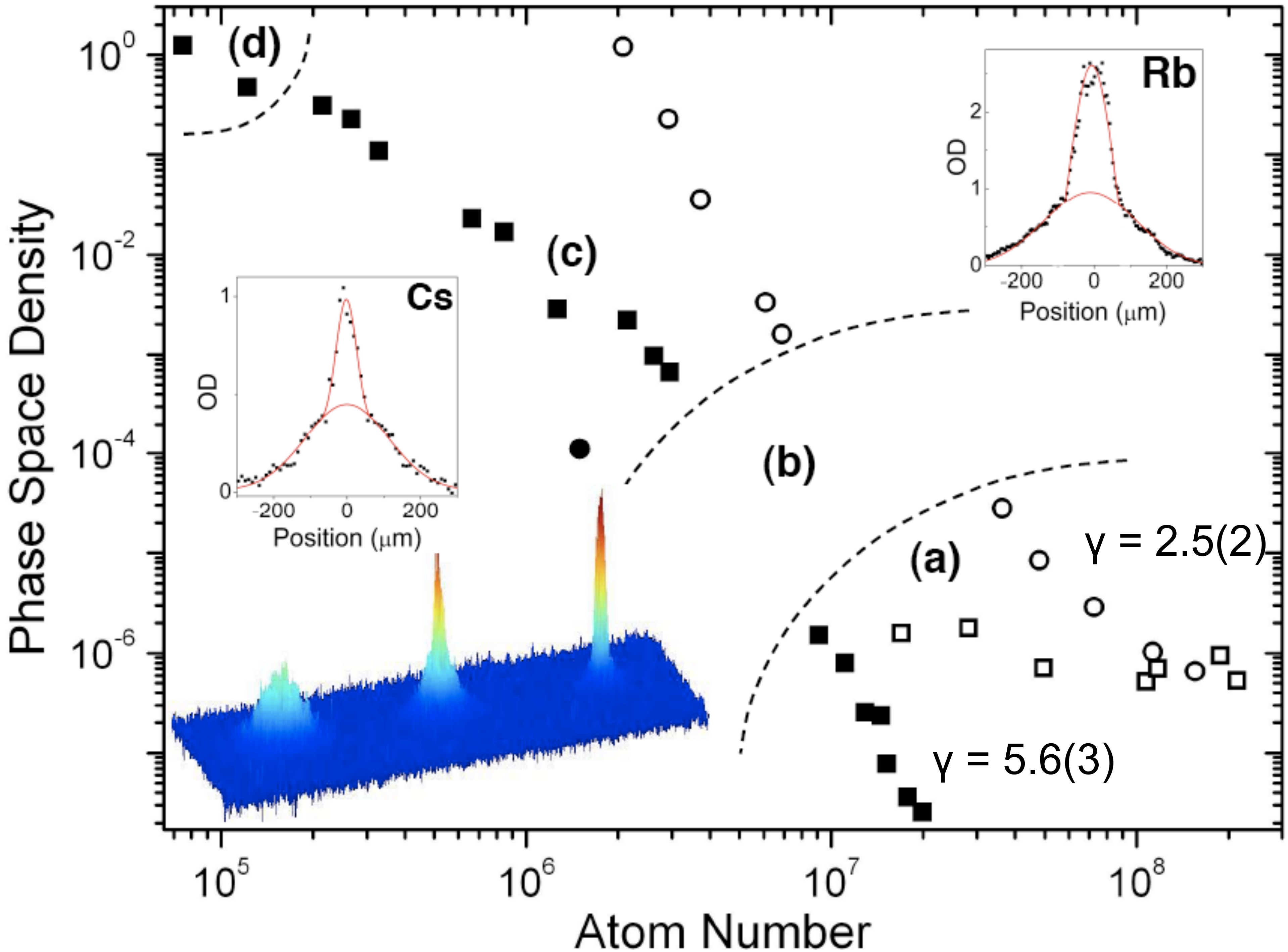

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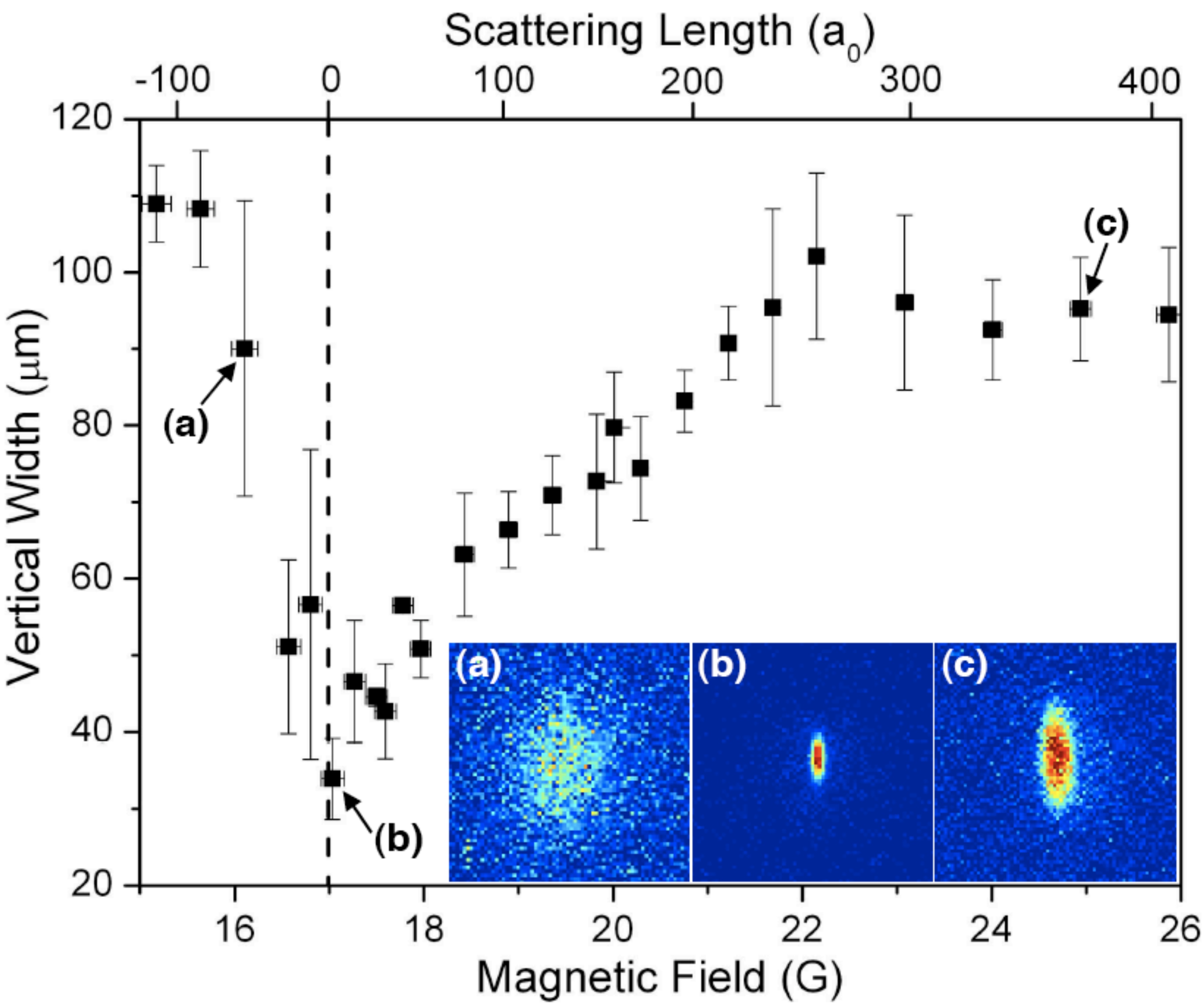

Vertical width of the ^{133}Cs condensate as a function of a magnetic field applied during a 50 ms time of flight expansion.

$$\mu = \frac{\hbar\omega_{h0}}{2}\left(\frac{15Na}{a_{h0}}\right)^{2/5} = m\omega_{h0}^2 R^2/2$$

(for a spherical trap)

Reviews of Modern Phys. 71, 463, 1999

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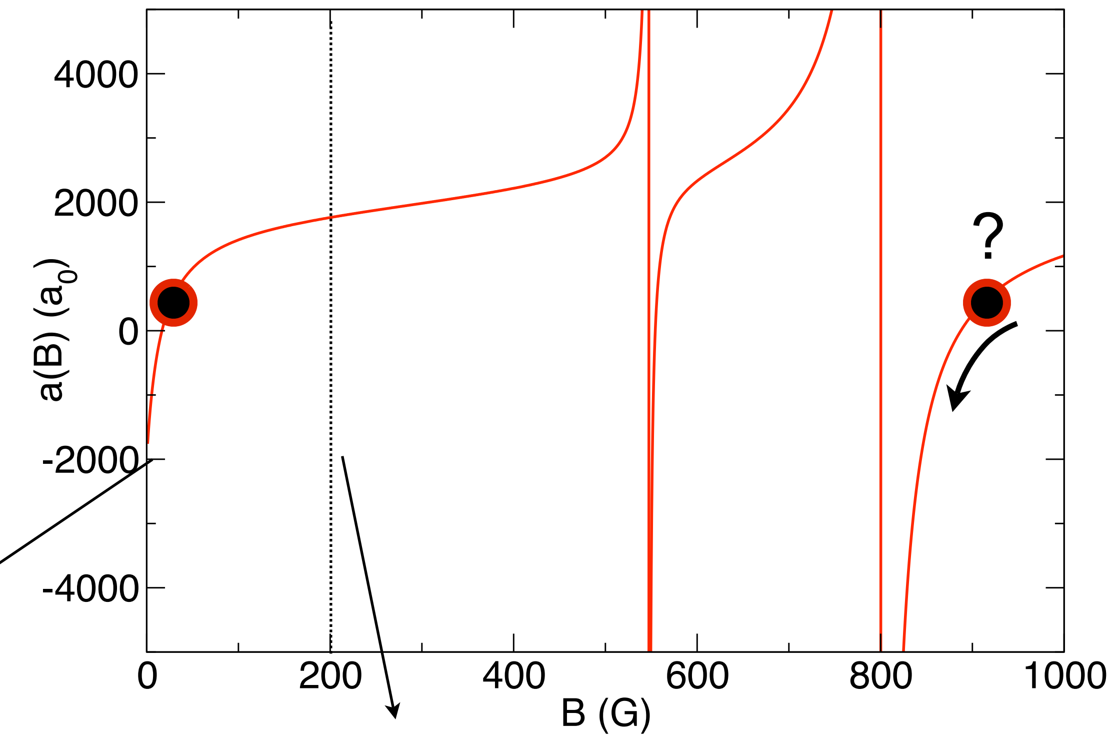

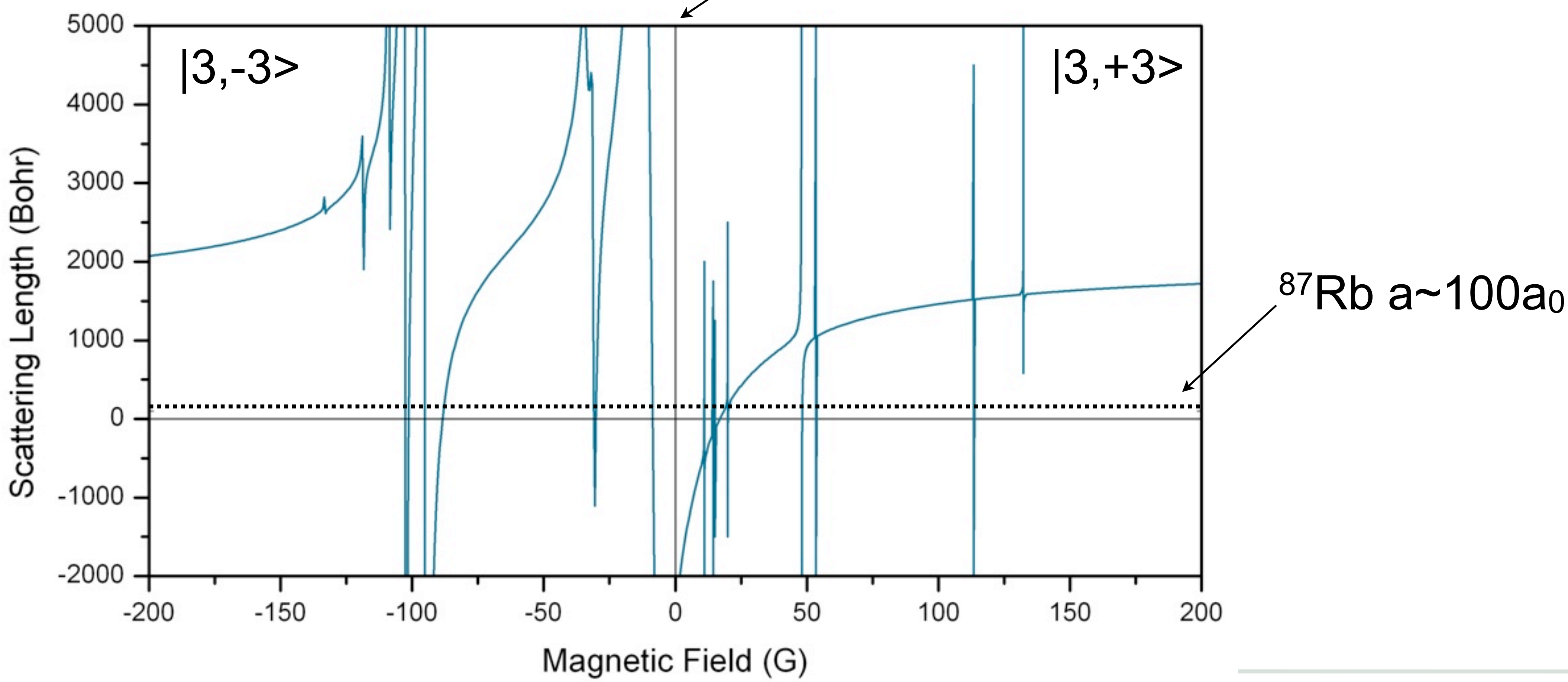

Cs_2 Molecules

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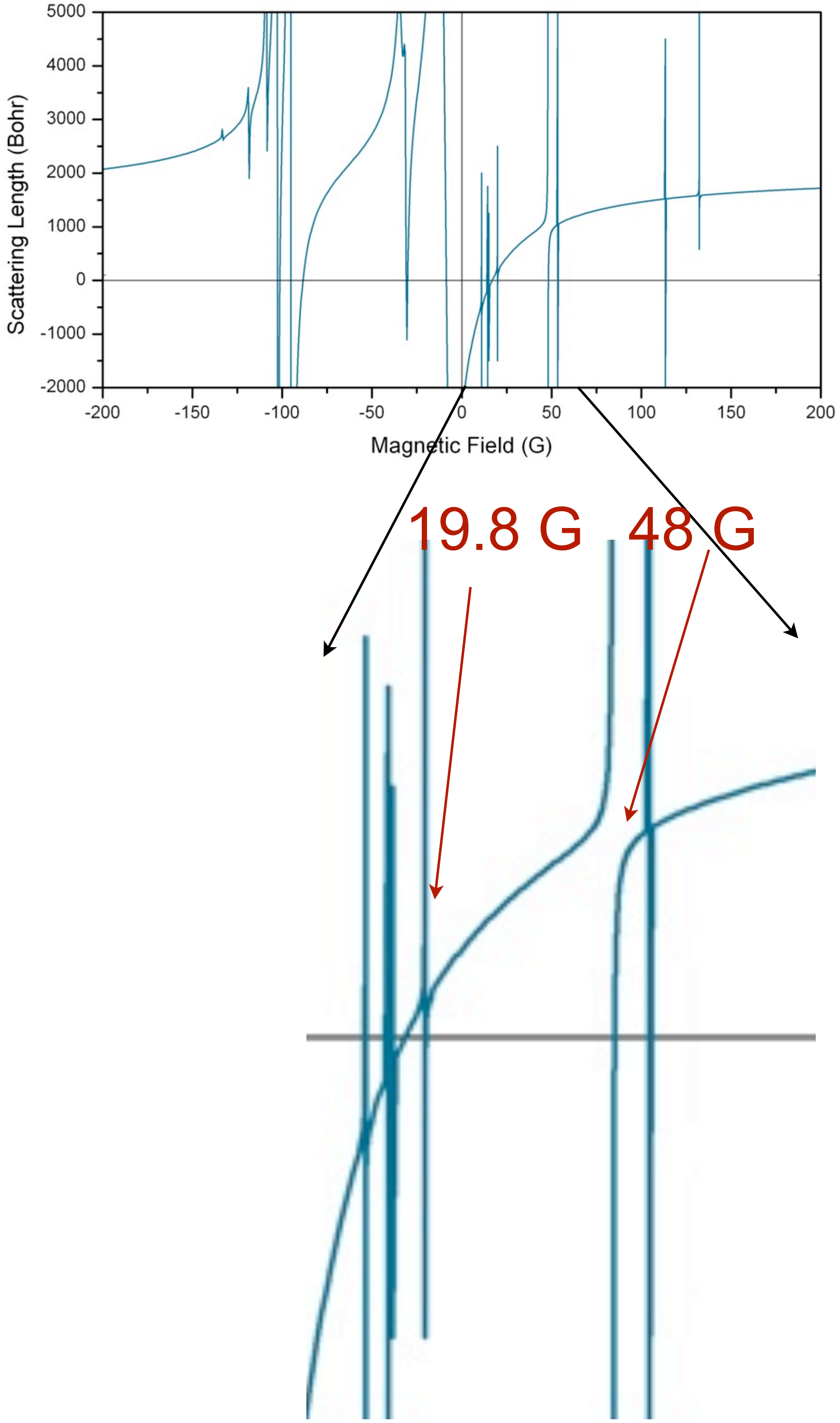

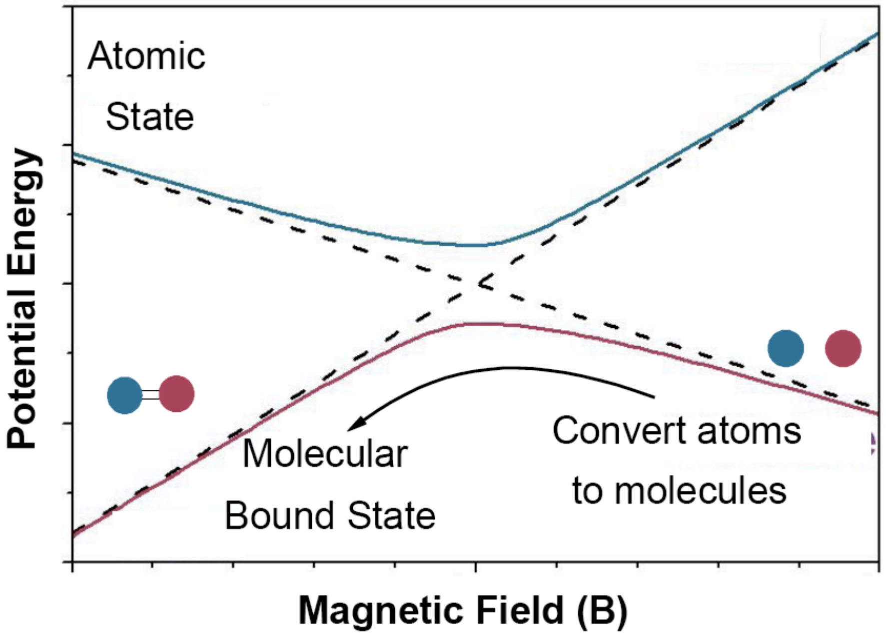

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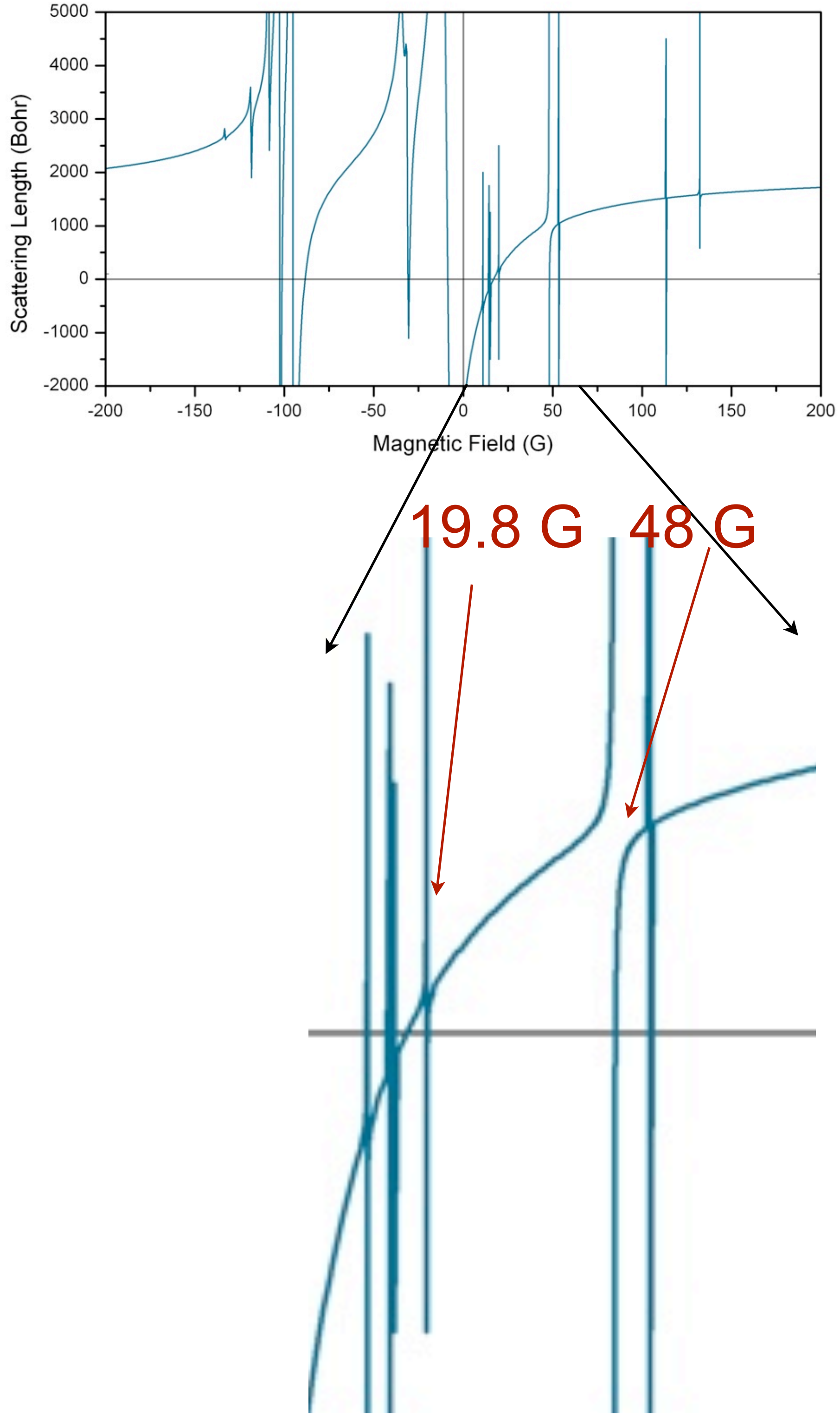

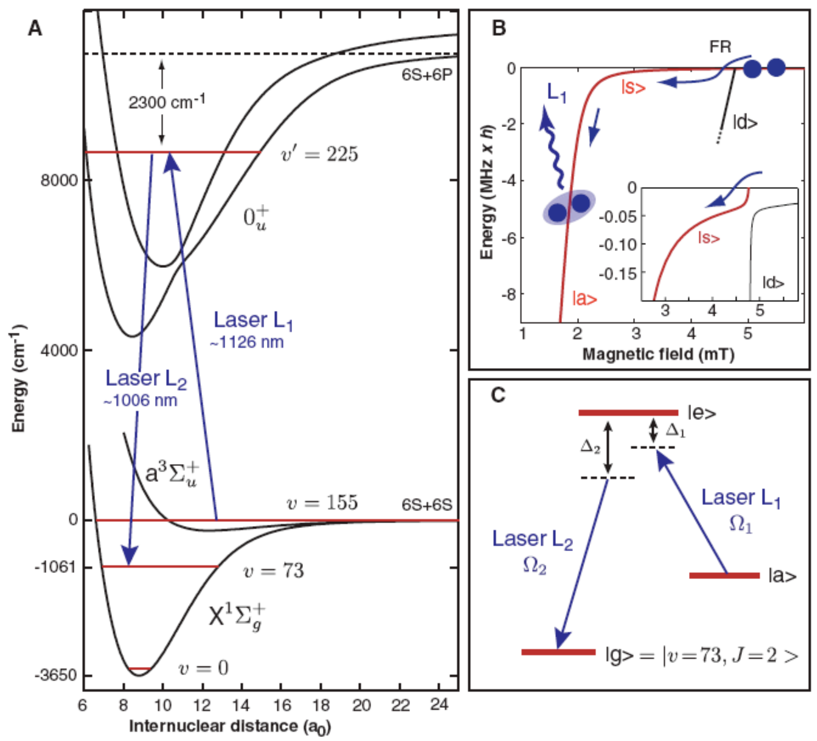

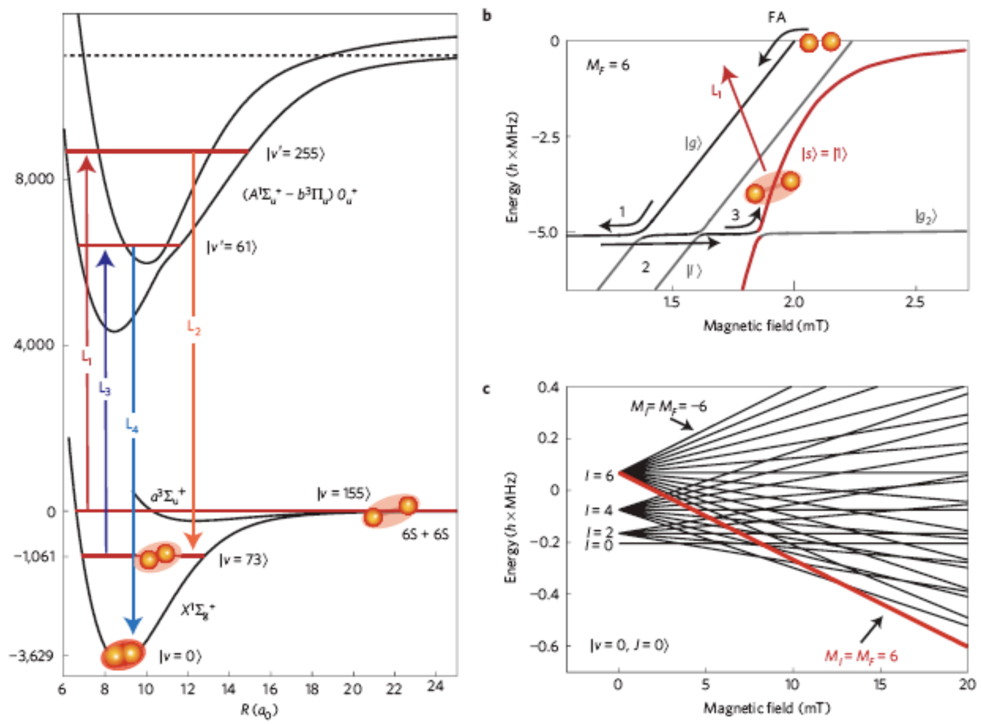

Innsbruck, Science 321, 1062 (2008) ; Nature Phys. 6, 265 (2010)

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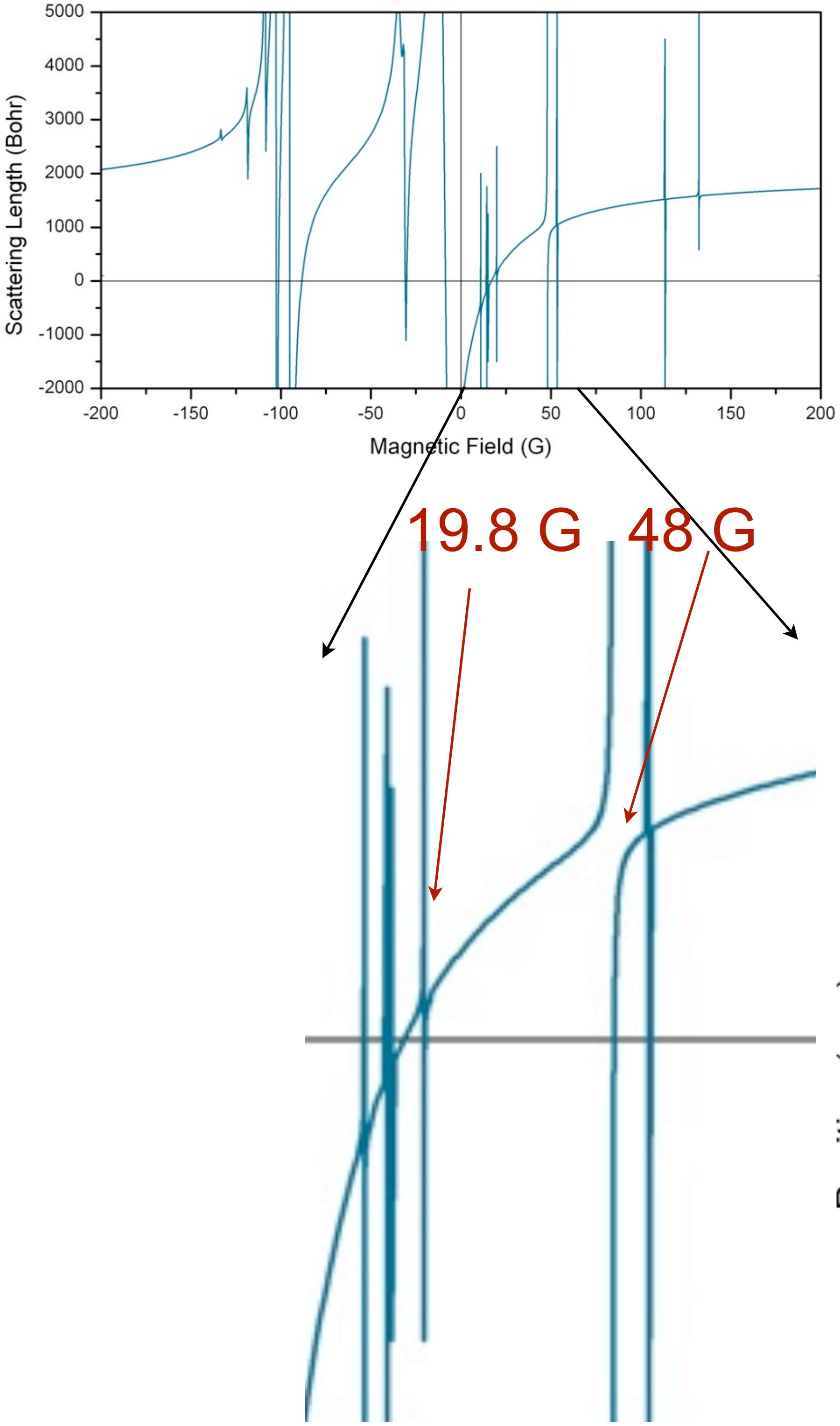
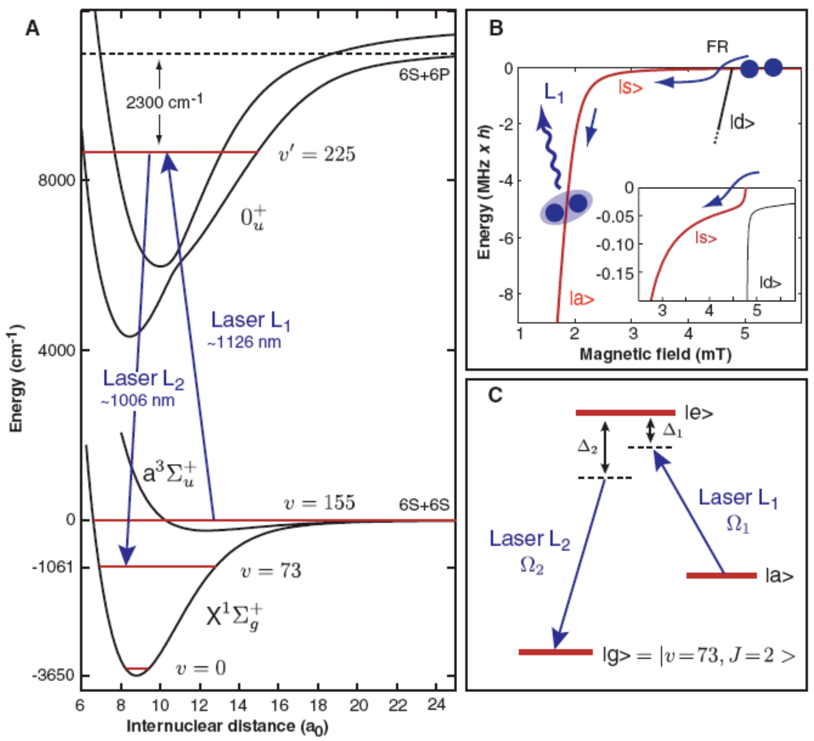
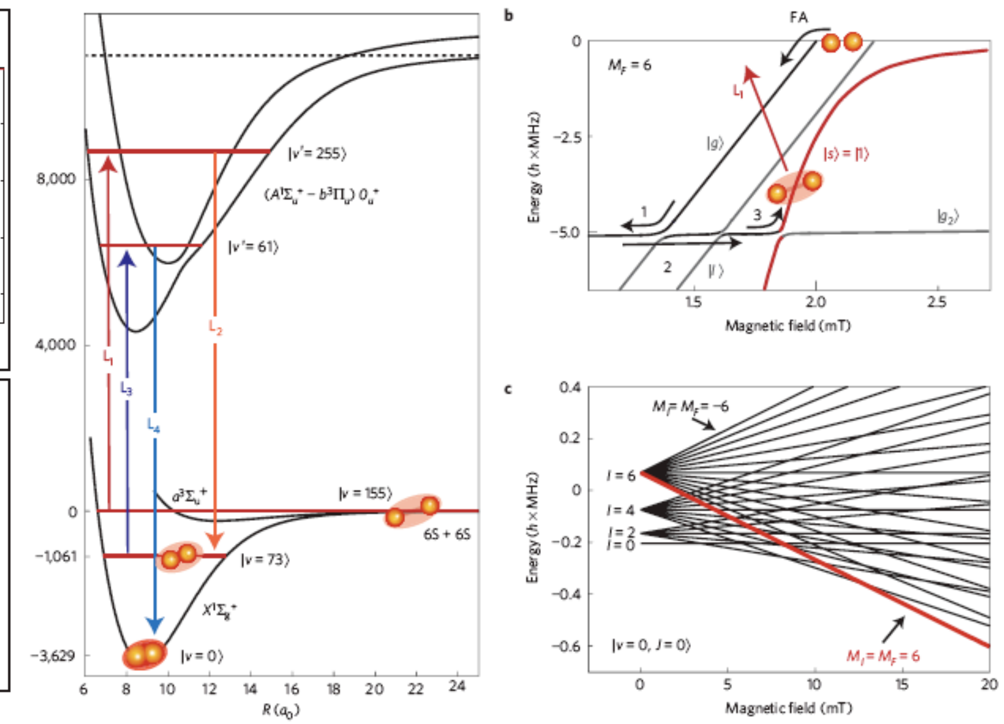
Cs$_2$ Molecules







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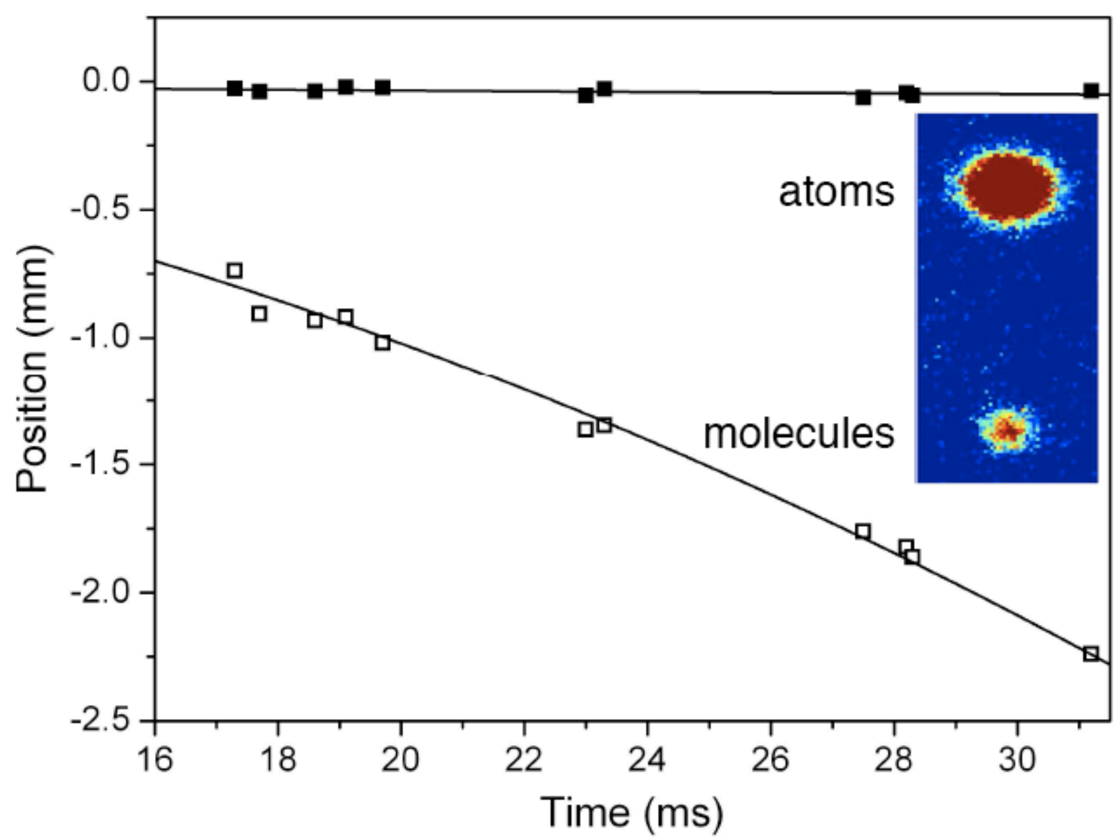

- 4g(4) Feshbach resonance at 19.8 G (5mG wide), a cross rate of 47 G/s.
- Dissociate by 17 to 21 G in 130 μs.
- $N_{Cs2} = 7 \times 10^3$
- magnetic moment $\mu = 0.92(1)\ \mu_B$

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- Conclusion

Toward Dual BEC

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2) A strong interspecies loss after loading into the levitated dipole trap.
- τ_{Cs}= 0.8(1) s, τ_{Rb}= 4(1) & 70(10) s.
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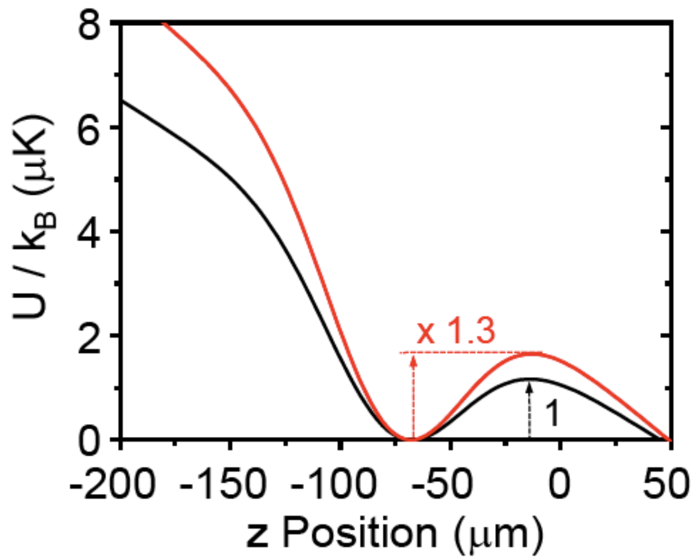
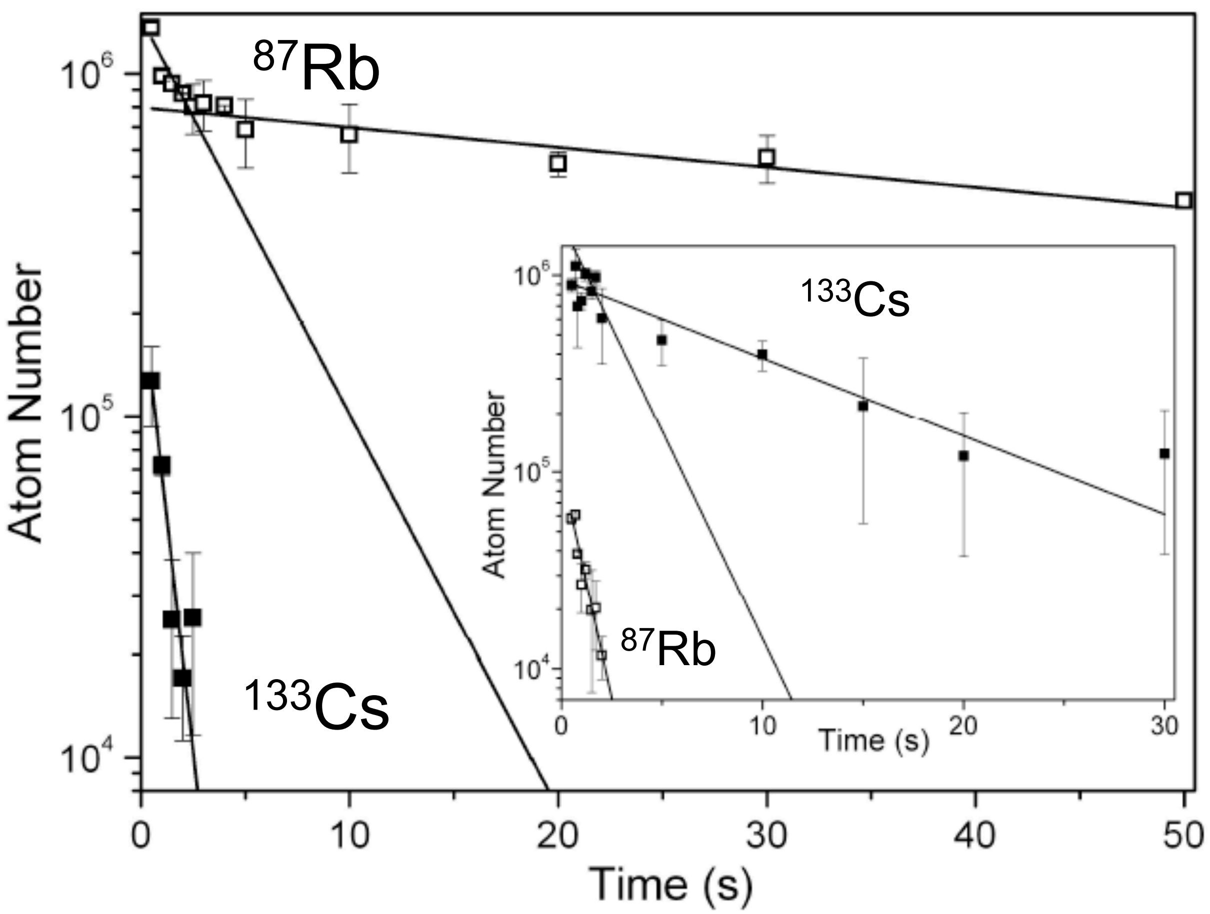
lower 3 body loss by reduce the peak density

$$\frac{\dot{N}}{N} = -L\langle n^2\rangle \; , L_3 = n_l C\frac{\hbar}{m}a^4$$

- change to a larger beam waist
- decompress trap





arXiv:1102.1576

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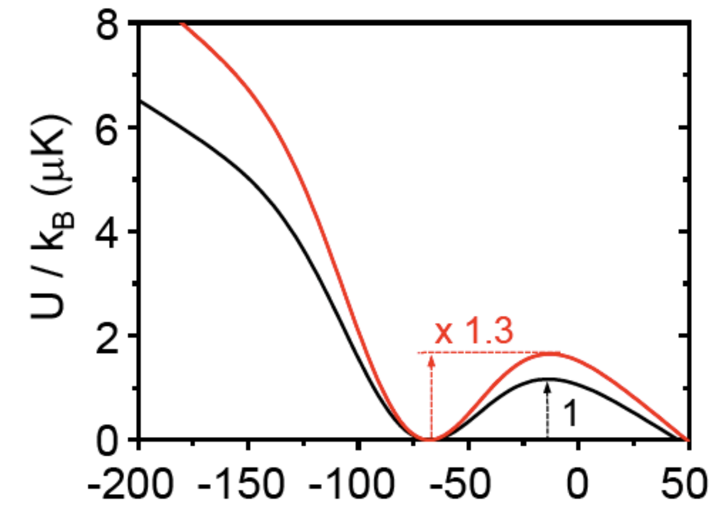

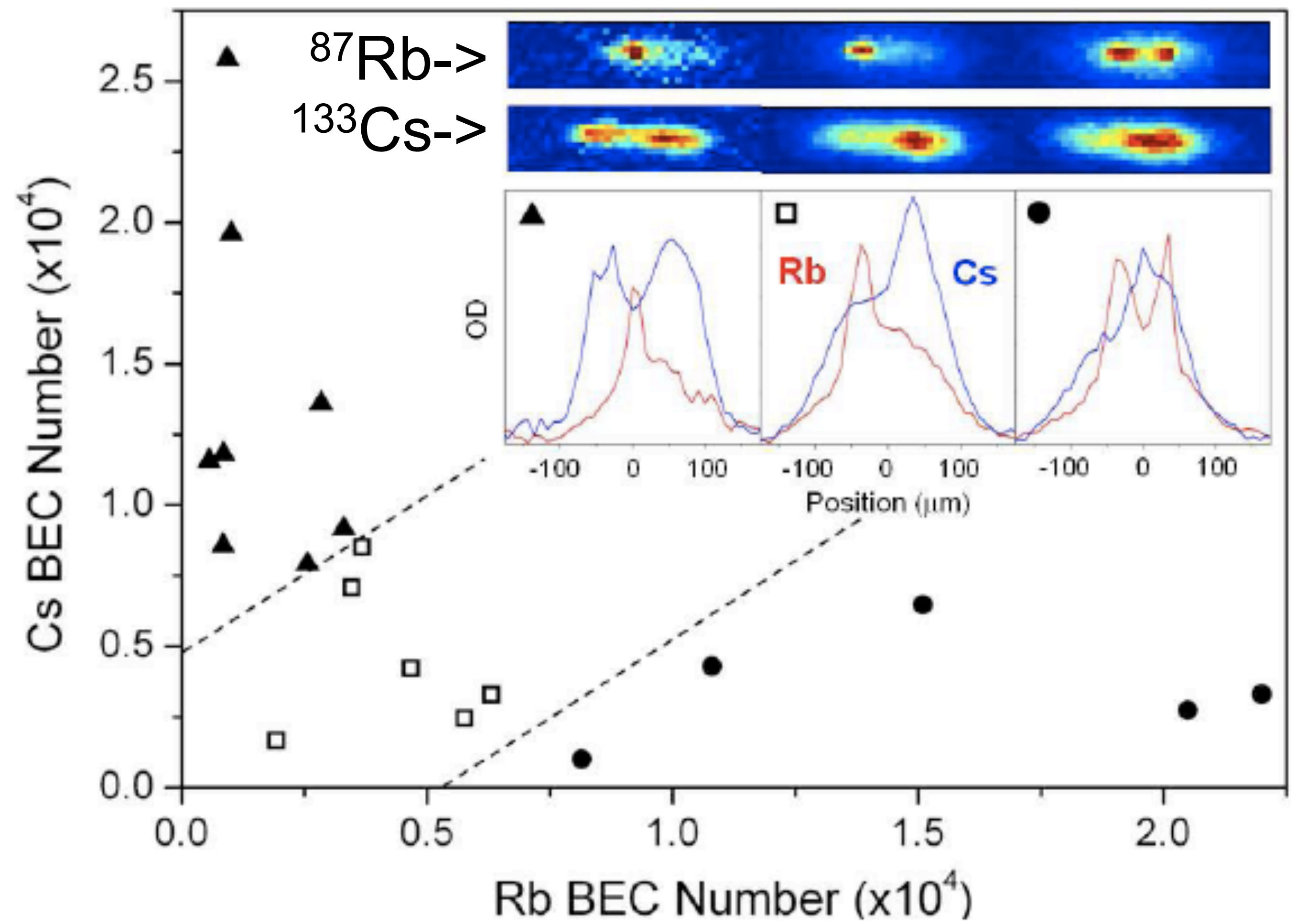

Toward Dual BEC

AtMol. Durham Atomic & Molecular Physics

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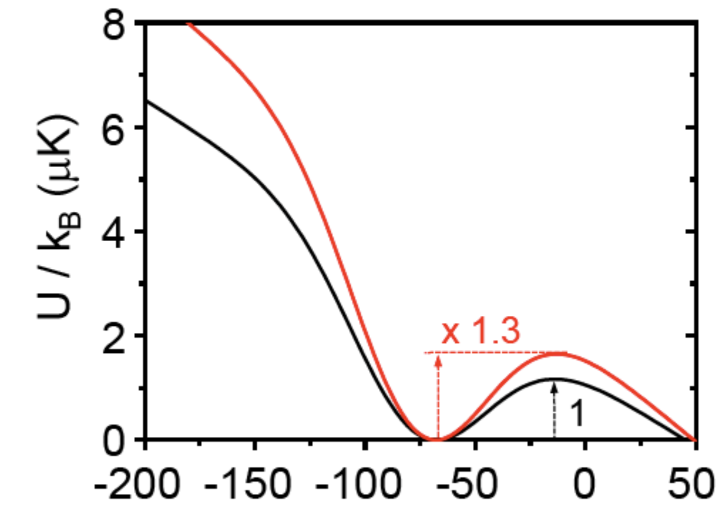

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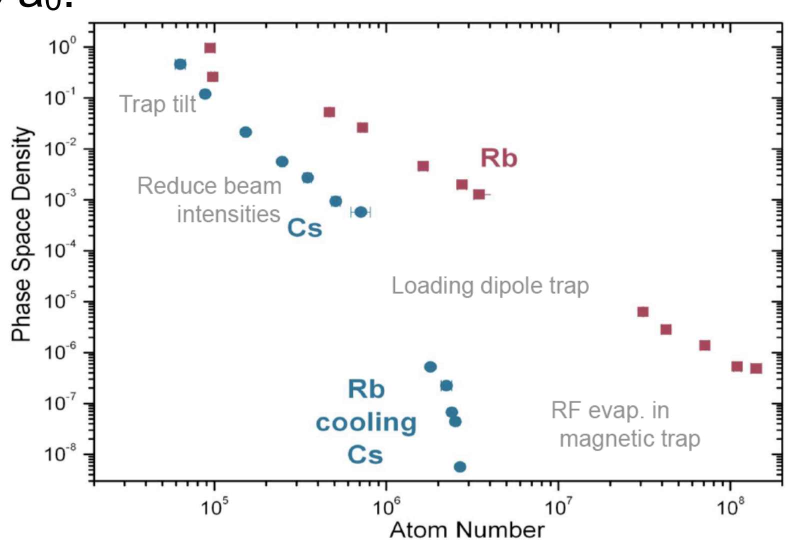
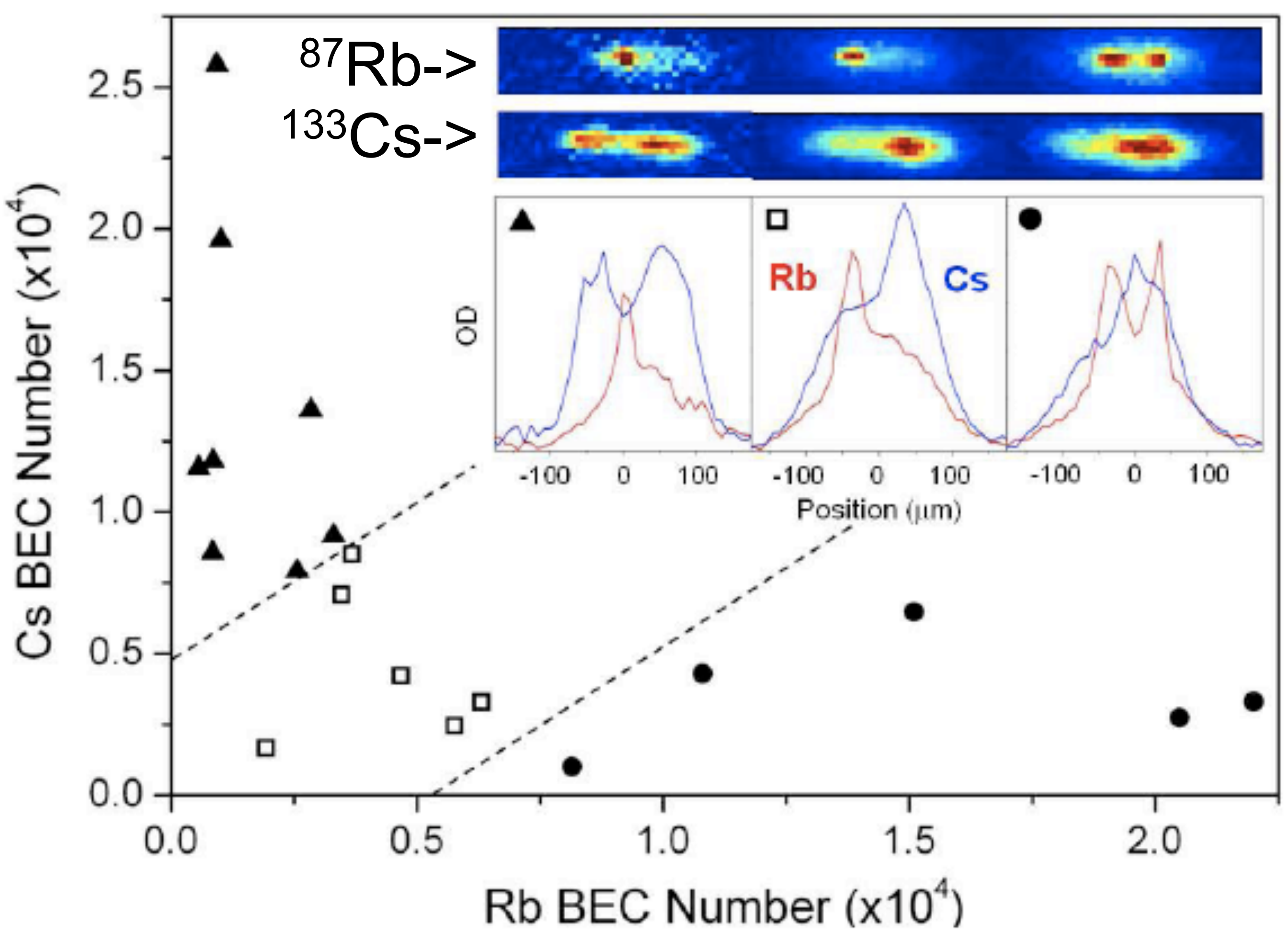
Immiscible quantum degenerate mixture:
the relative strength of the atomic interactions

$$\Delta = \frac{g_{RbCs}}{g_{Rb} g_{Cs}} > 1, g_{ij} = 2\pi\hbar^2 a_{ij} \left(\frac{m_i + m_j}{m_i m_j}\right)$$

Phys.Rev. A, 65, 063614, 2002

In our case, B = 22.4 G, a_{Rb} = 100 a_0 and a_{Cs} = 280 a_0, the observation of immiscibility require a_{RbCs} > 165 a_0.





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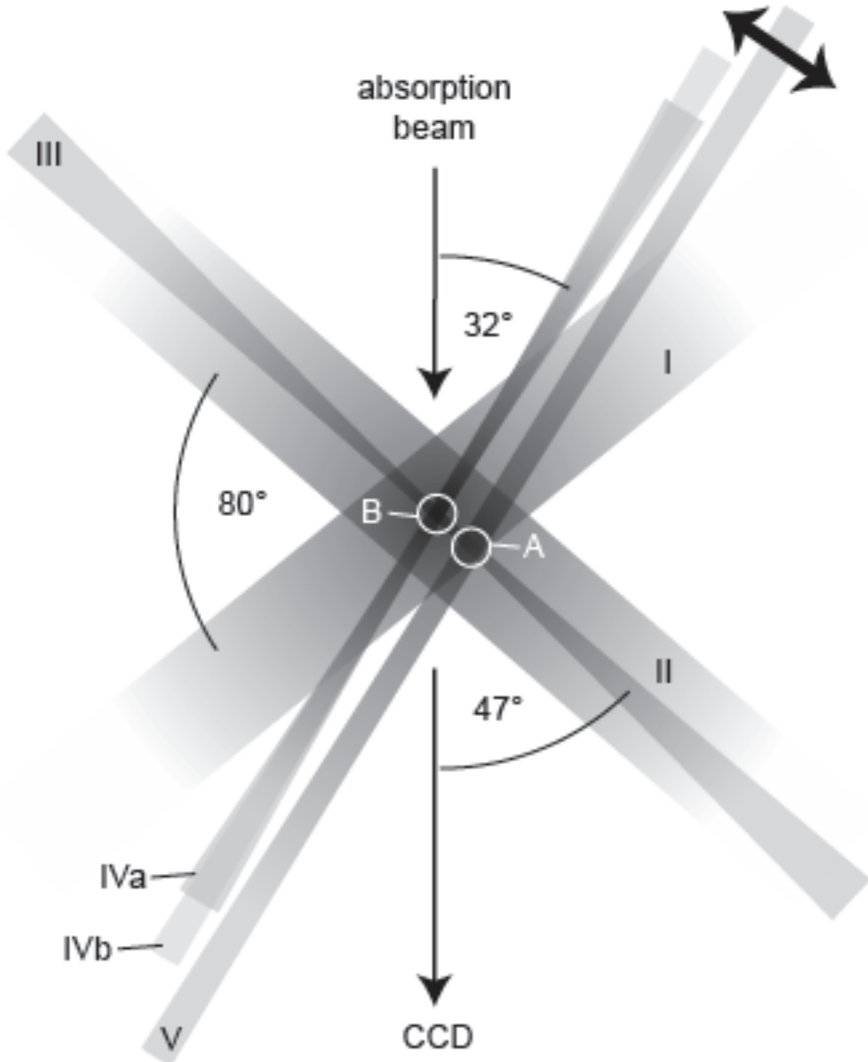
Durham University

Toward Dual BEC



Innsbruck, H.C. Nagerl's group:

BECs of ^{87}Rb and ^{133}Cs atoms in separate optical traps [arXiv:1101.1409]

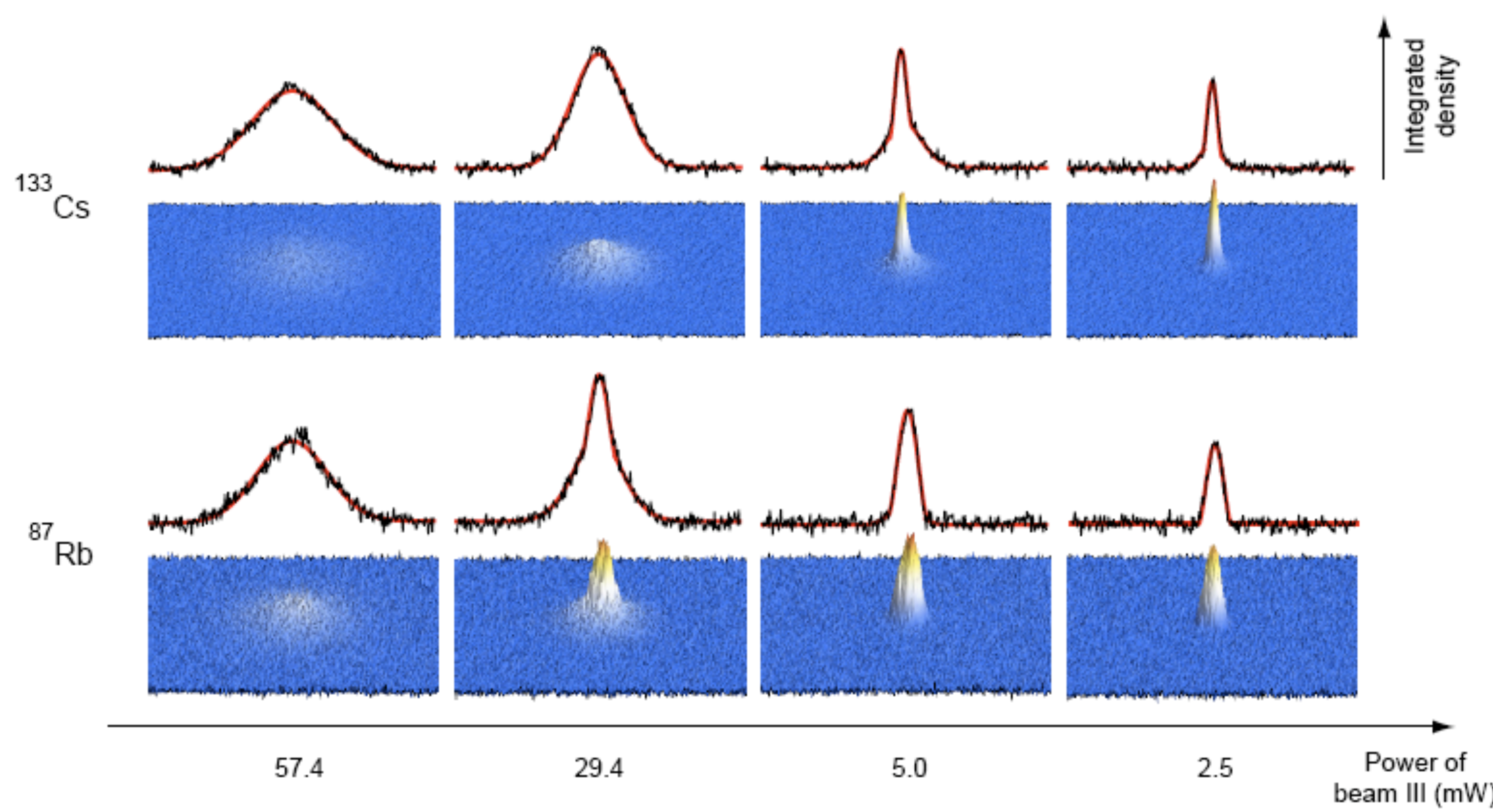
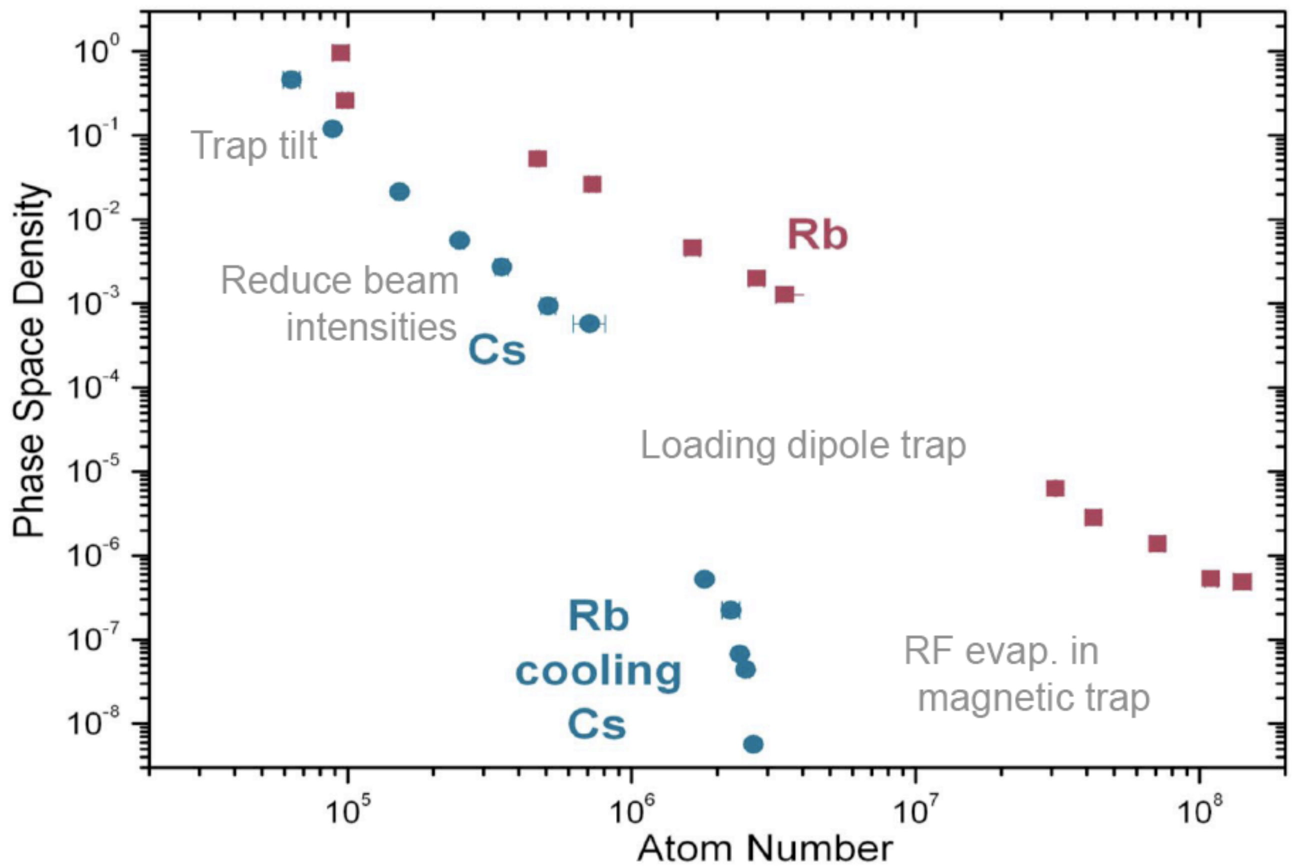


Table 1. Initial trap parameters. The waist radius given here is the $1/e^2$ intensity radius.

Beam	I,II	III	IVa	IVb	V
Wavelength (nm)	1070	1064.5	820	1064.5	1064.5
Waist radius (μm)	500	45	66	57	102
Rb depth / k_B (μK)	13	8.5	24	10	6.0
Rb rad. freq. (Hz)	23	204	234	176	77
Cs depth / k_B (μK)	24	15	-25	18	11
Cs rad. freq. (Hz)	25	220	192i	189	83

RbCs Feshbach Resonance



Accepted by Eur. Phys. J. D, (2011)

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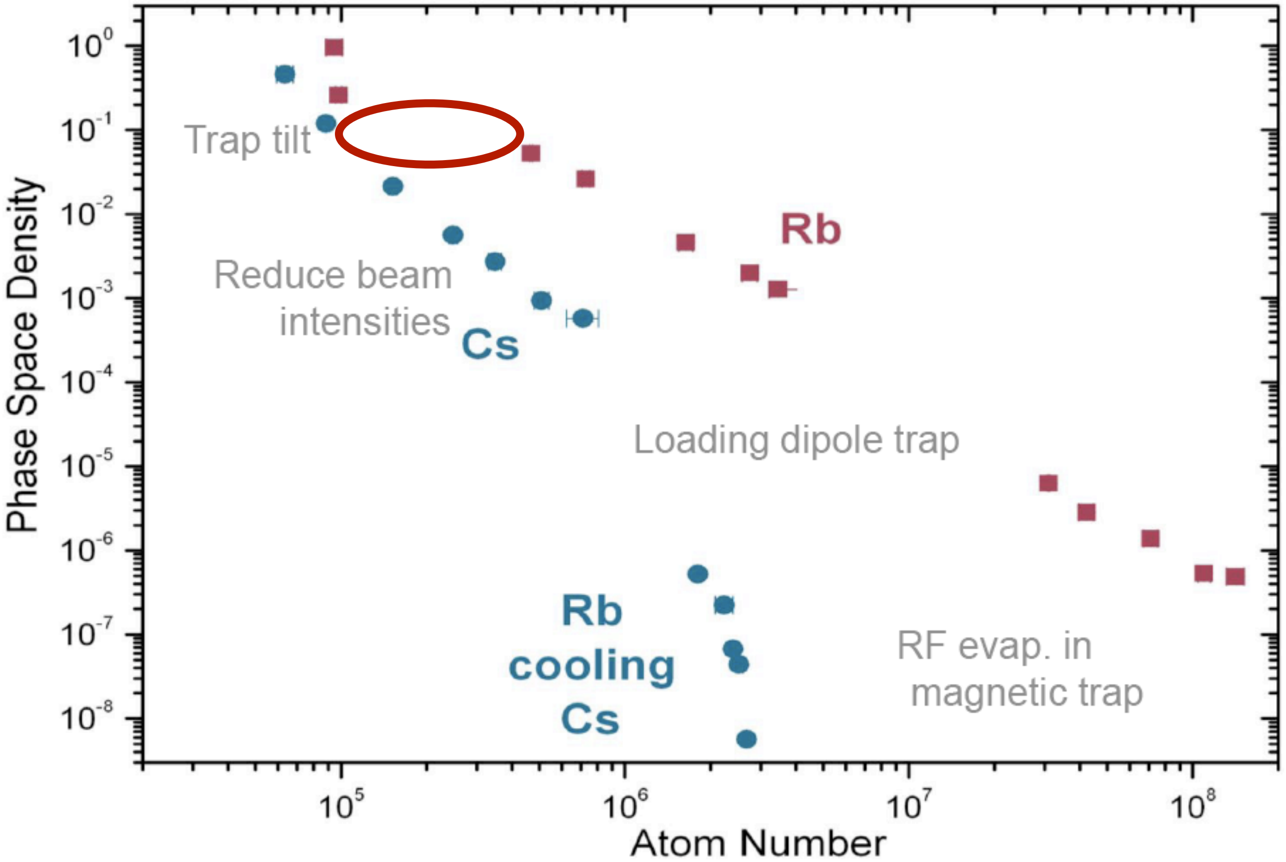

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RbCs Feshbach Resonance

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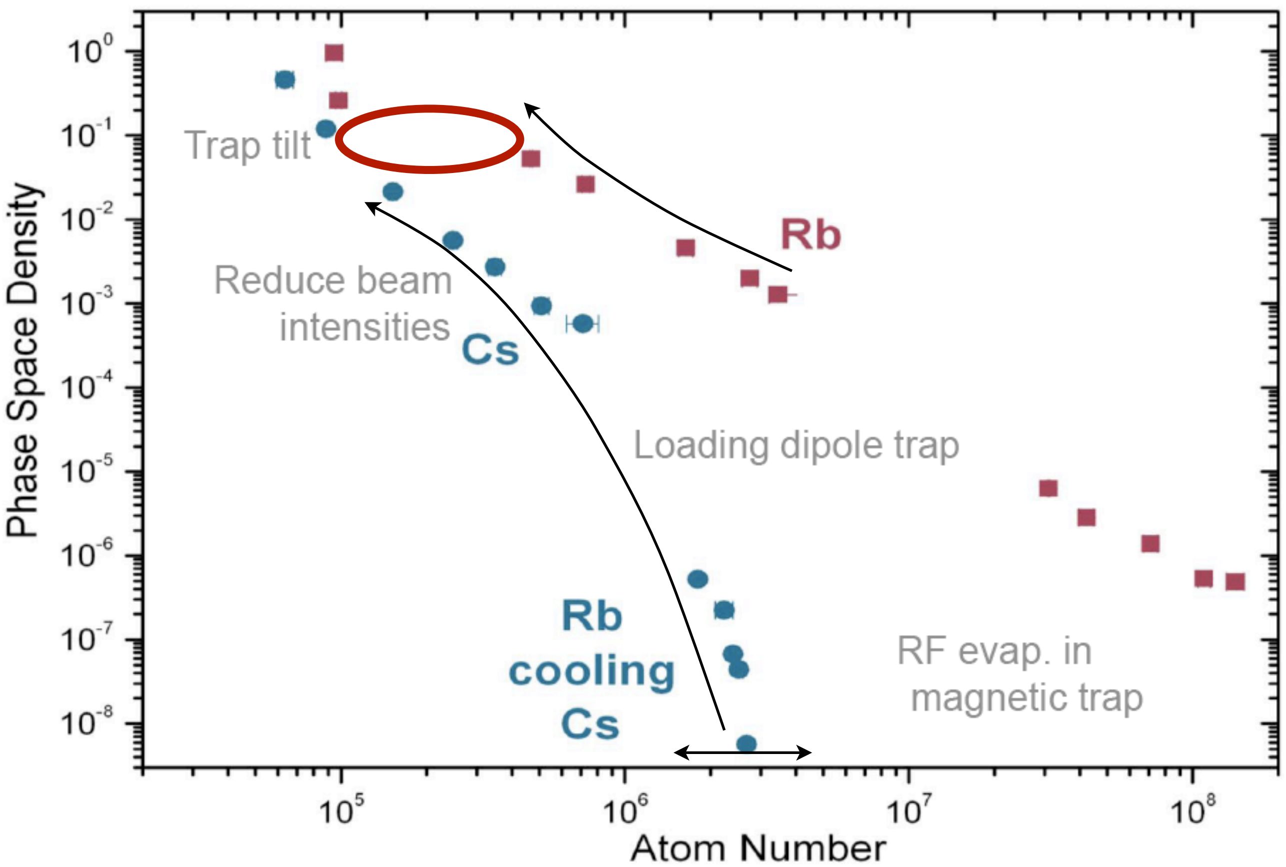

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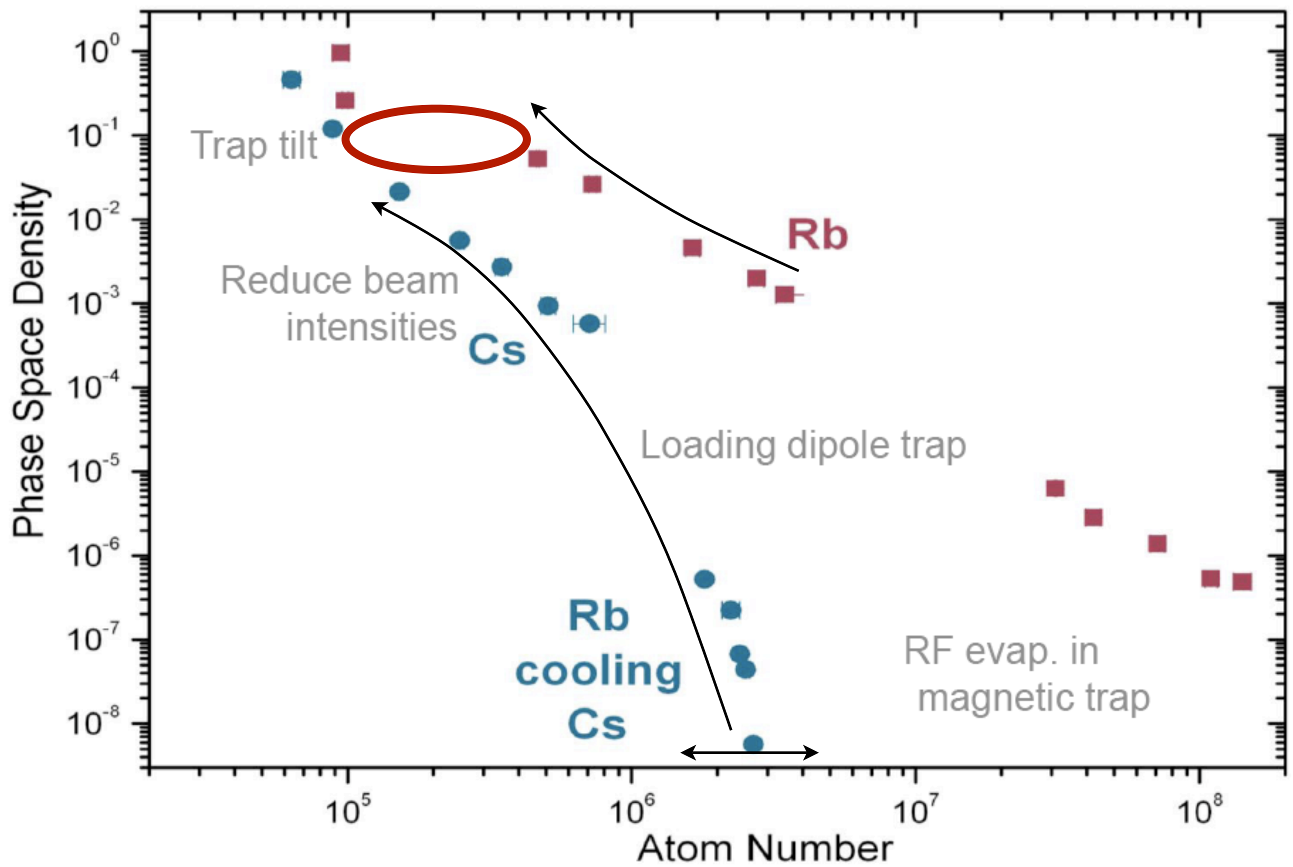

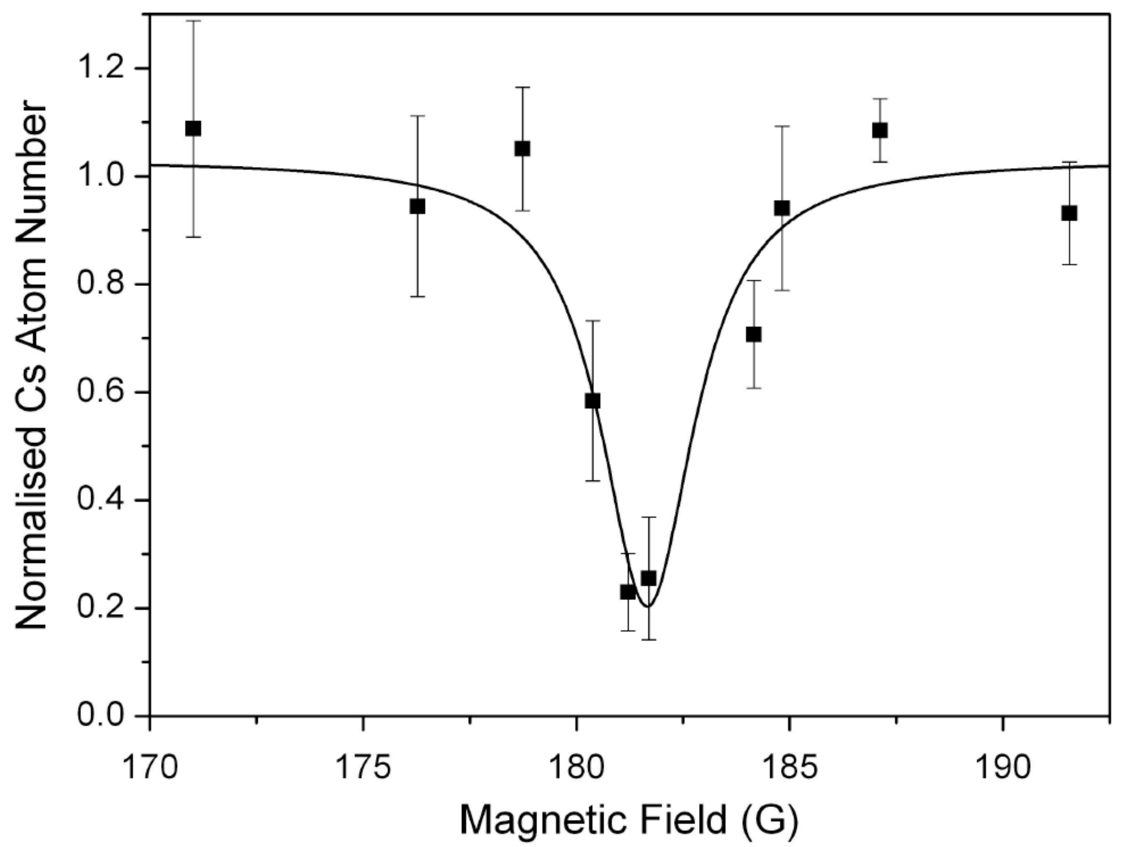

Peak densities of ^{87}Rb and ^{133}Cs are 1.6(1) x 10^{12} cm^{-3} and 3.1(4) x 10^{11} cm^{-3}.

The mixture contains 3.0(3) x 10^5 ^{87}Rb and 2.6(4) x 10^4 ^{133}Cs at 0.32(1) μK

- the temperature is well below the p-wave threshold (k_B x 56 μK based upon C_6, Phys. Revs A 59, 390, 1999)
- The presented Feshbach spectrum near 180 G is measured by evolving the mixture at a specific homogeneous magnetic field for 5 sec and each data point corresponds to an average of 3-5 measurments.

Durham University

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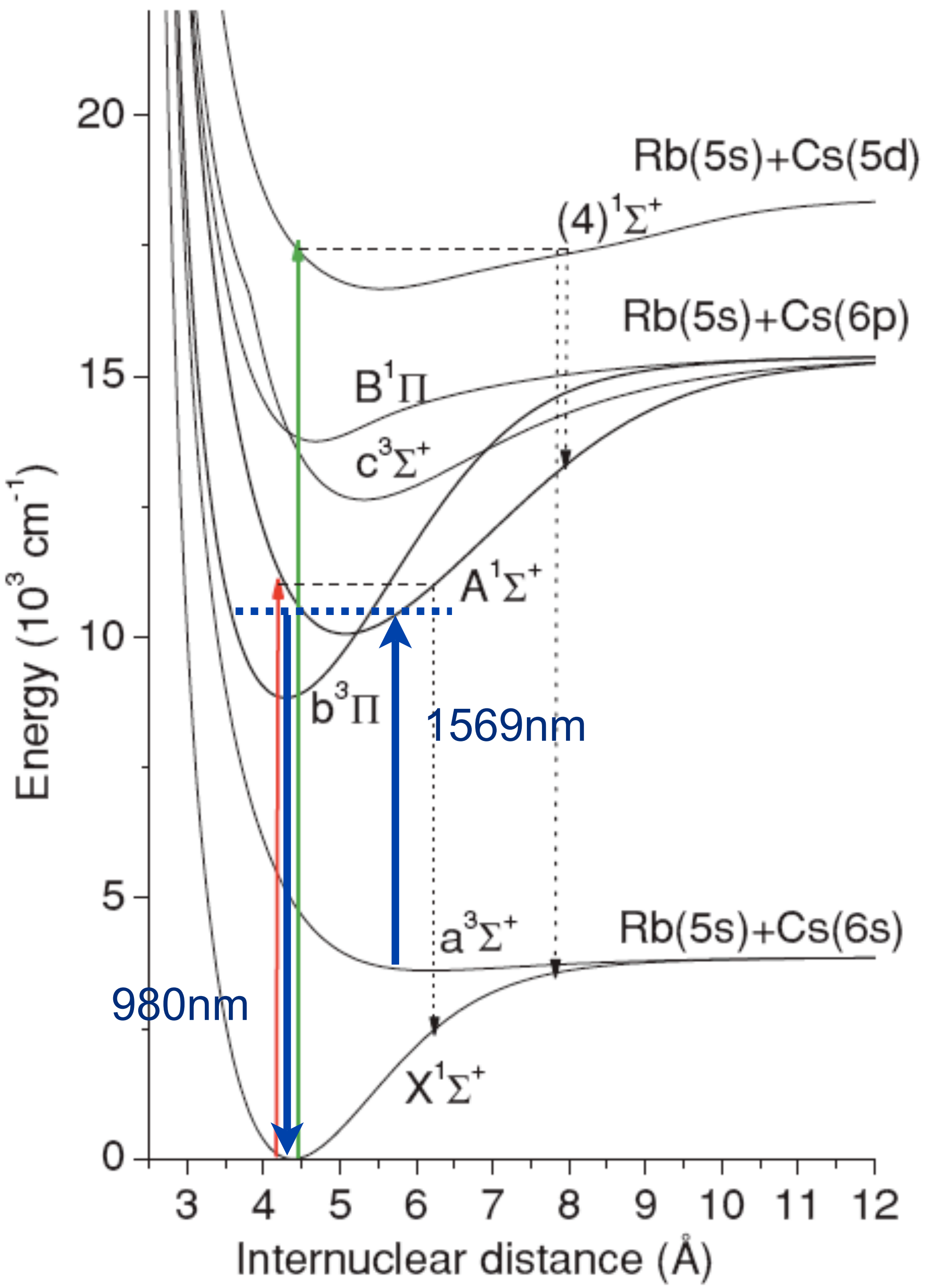
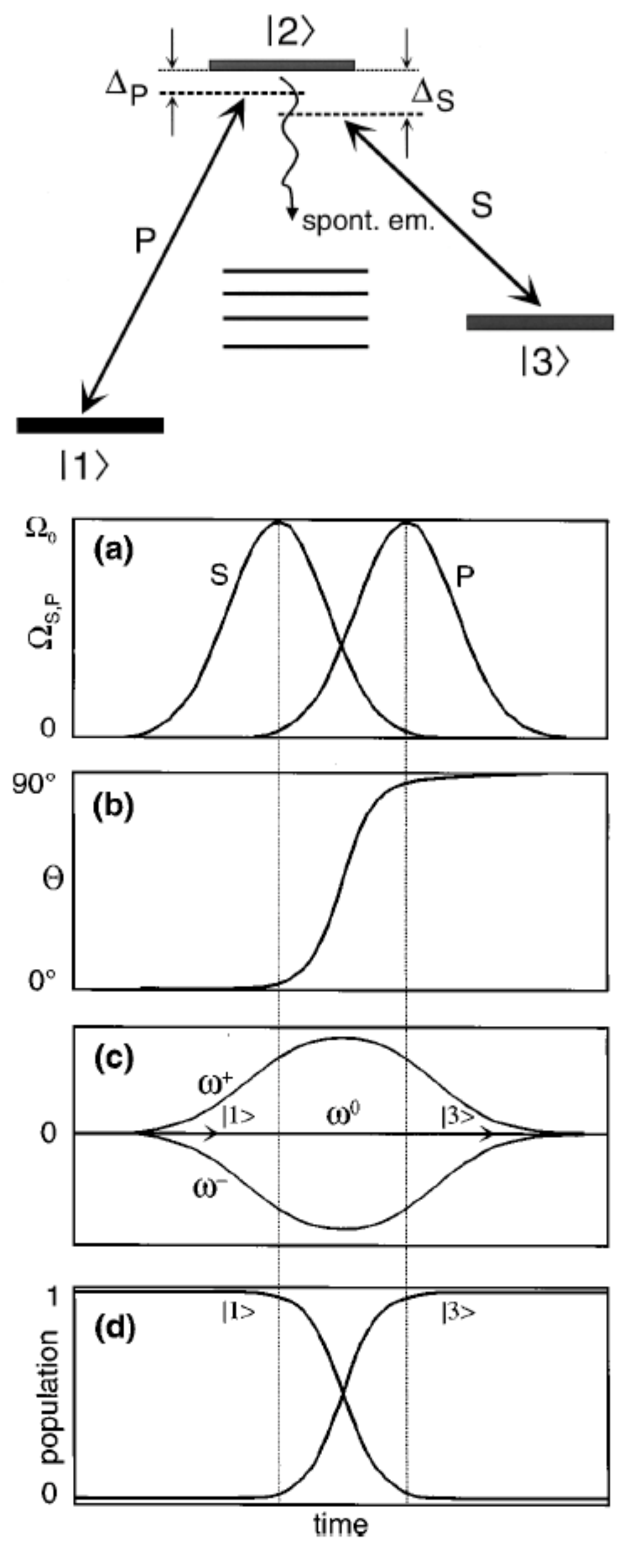
Outline

- Bose-Einstein condensation of ^{87}Rb BEC
  - in a combined magnetic and optical trap
  - in a levitated crossed dipole trap
- Bose-Einstein condensation of ^{133}Cs
  - a new method for the production of ^{133}Cs BEC
  - demonstrate the creation of Cs_2 molecules via magneto-association on the 4g(4)
- A quantum degenerate Bose Mixture of ^{87}Rb and ^{133}Cs
  - observe a striking phase separation of the two species
  - observation of an interspecies Feshbach resonance at 181.7(5) G
- Stimulate Raman adiabatic passage (STIRAP)
  - a two-photon transition can used to transfer the Feshbach molecules into the rovibrational ground state or a more deeply bound state
- Conclusion



Phys, Rev, A 81, 042511, 2010
(Aknar Lercher Thesis, Innsbruck 2010)



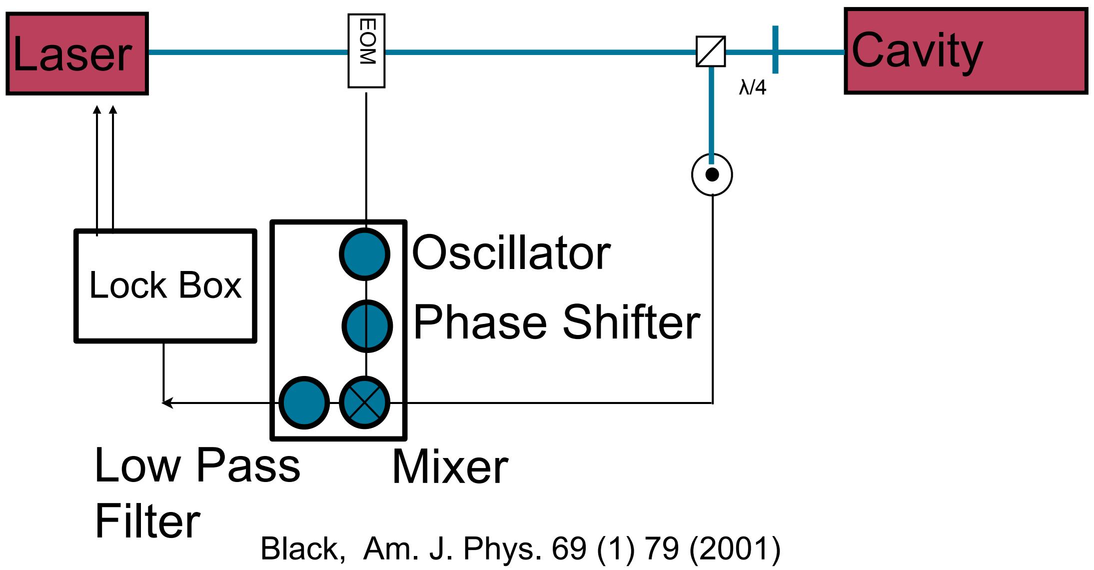
The adiabatic condition

$$\sqrt{\Omega_P^2 + \Omega_S^2}\Delta\tau >> 1$$

τ, the overlap period of two pulses.

Rev. Mod. Phys 70, 1003, 1998

Pound-Drever Hall signal



Black, Am. J. Phys. 69 (1) 79 (2001)

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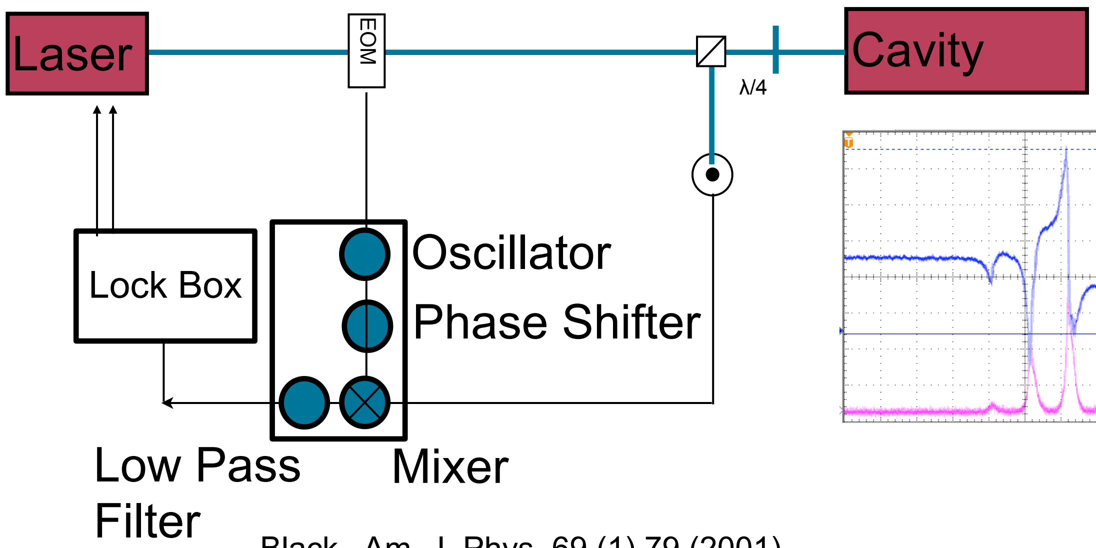

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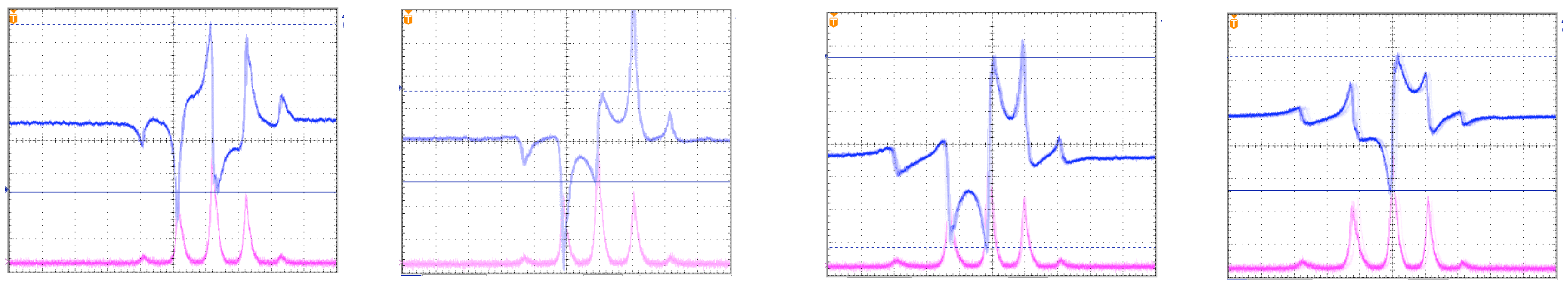

STIRAP

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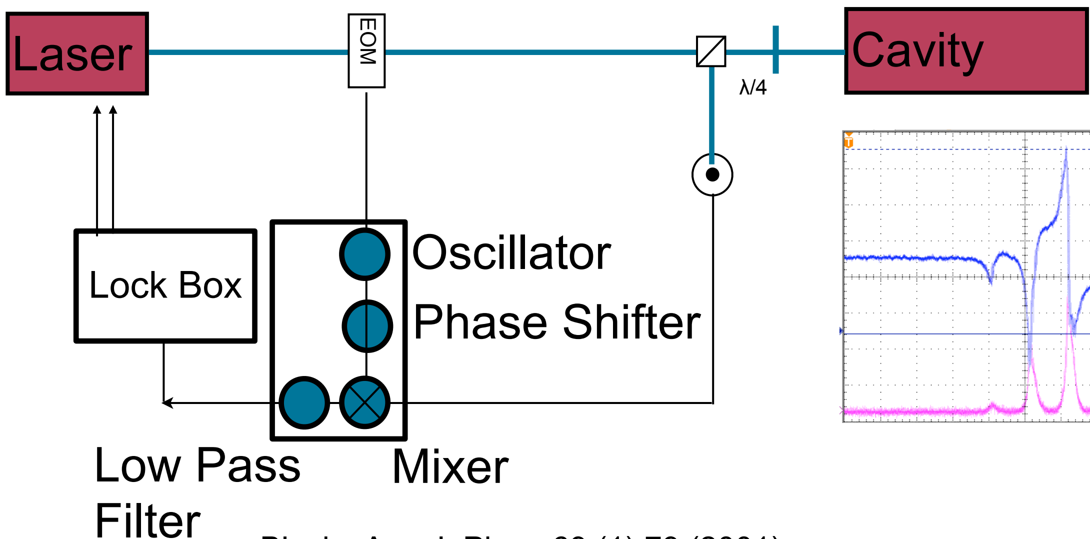

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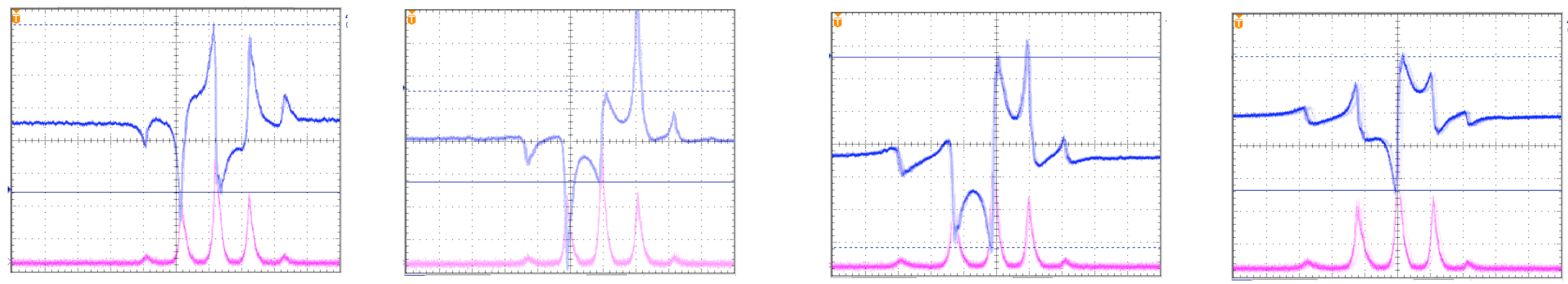
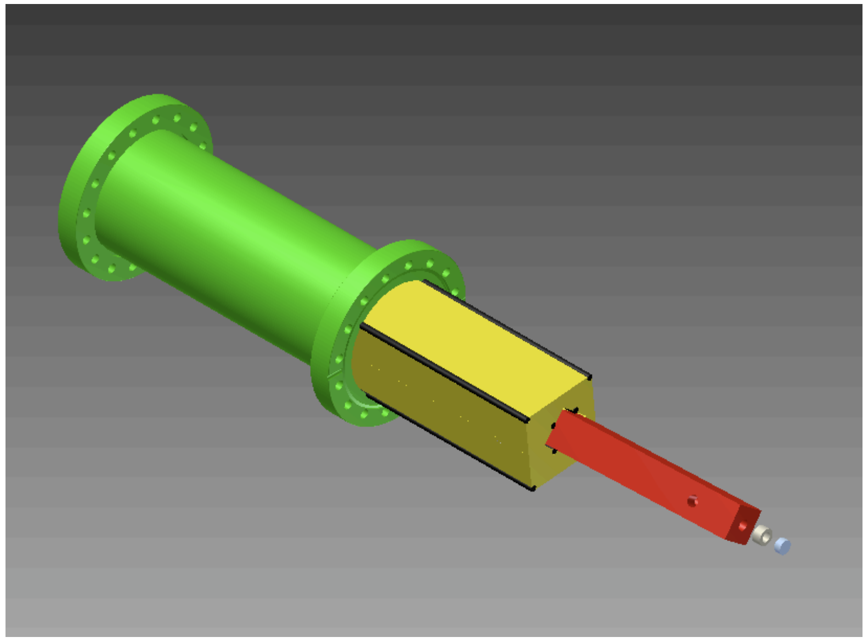


High Finesse of 3000 → R ~99.91%
υ_{FSR} = 750 MHz, cavity length= 20 cm
$\delta\upsilon$=250 kHz
(One planar mirror and one concave mirror r=50 cm)



STIRAP

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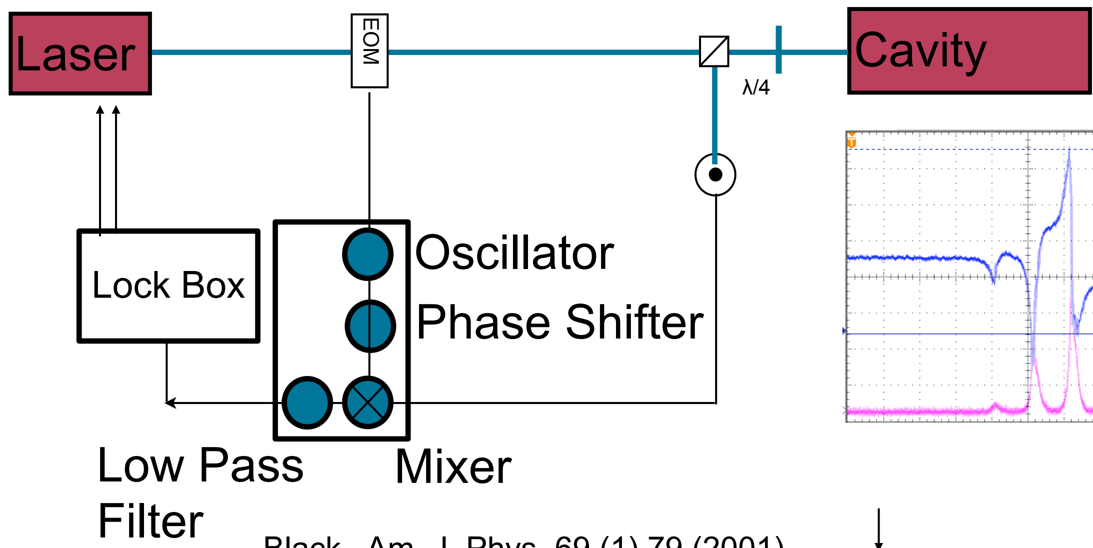

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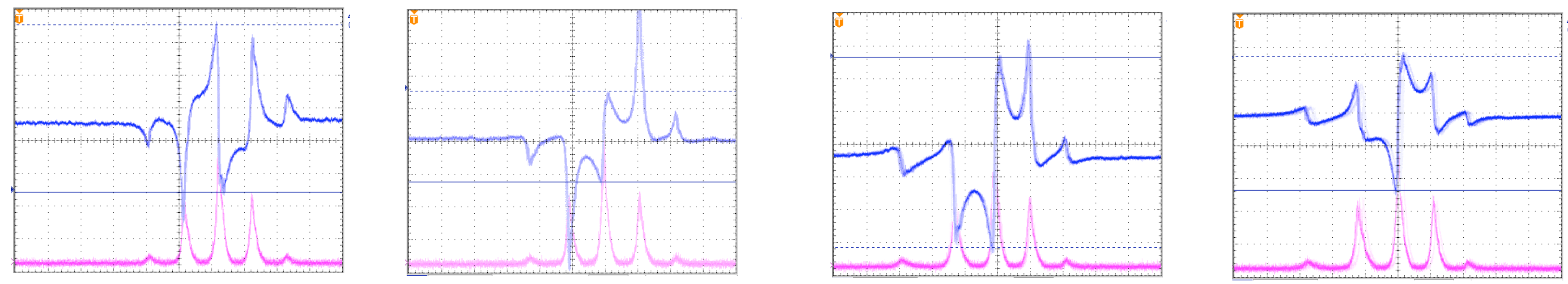

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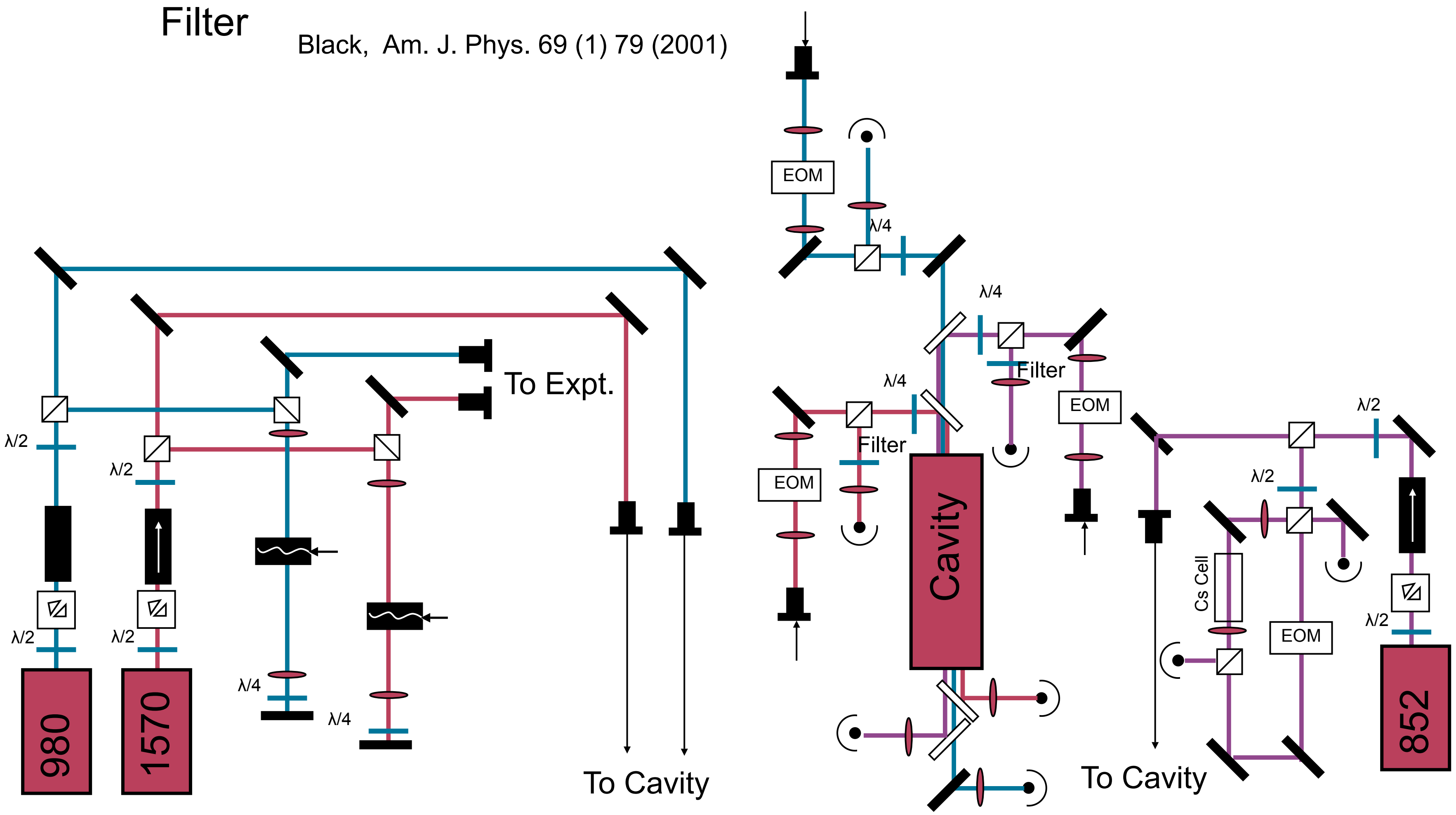

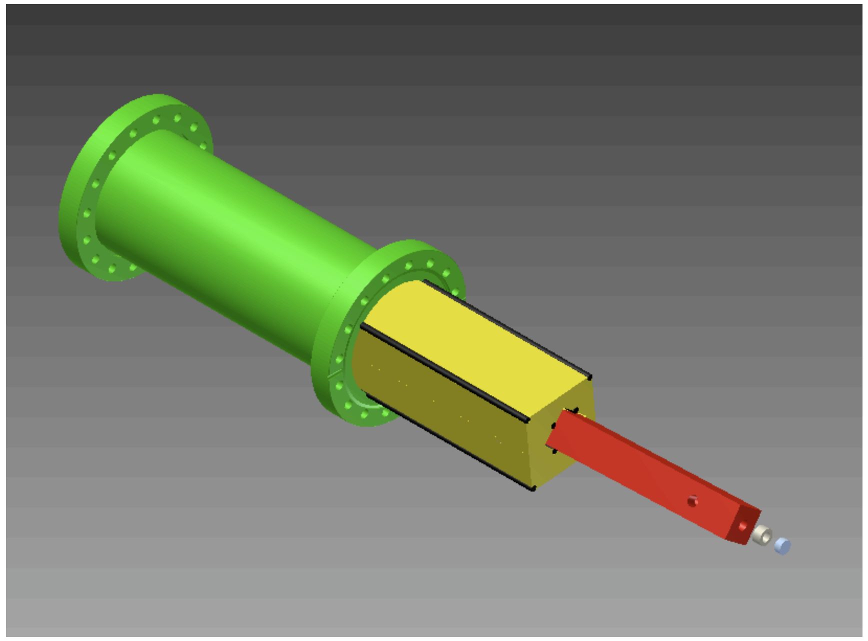

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  - two ECDLs (1569nm and 980nm) will be locked to a reference cavity which is stable by a reference ECDL (852nm).

Acknowledge

Steve Danny Dan Kirsteen Michael