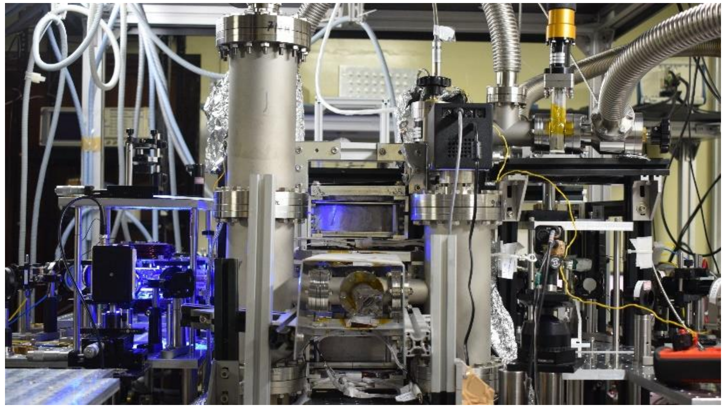
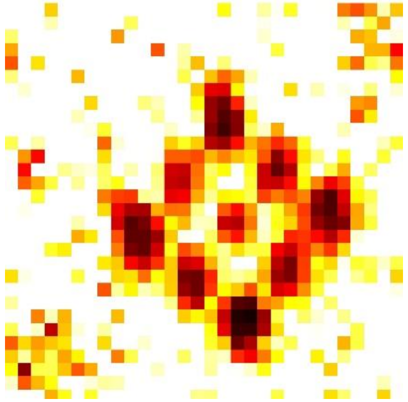
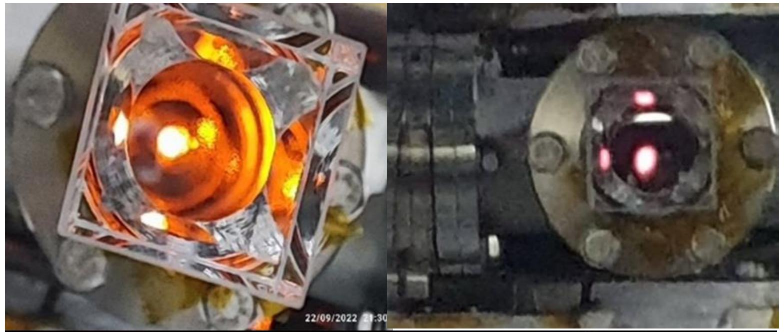
Real-time detection of cold atoms for quantum computing and sensing

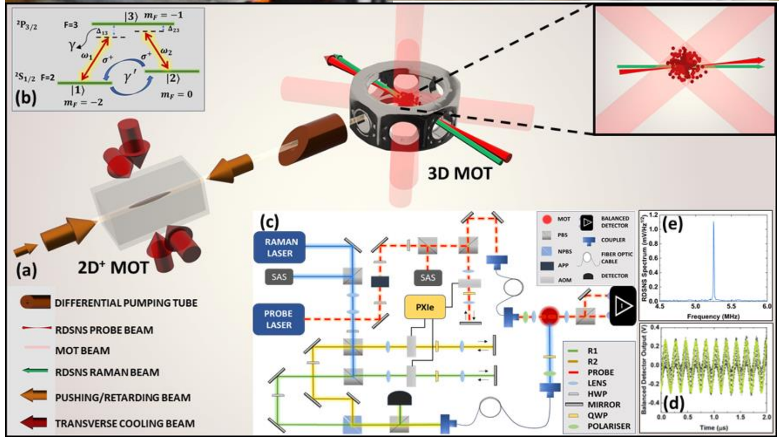
Saptarishi Chaudhuri, QuMiX Laboratory, RRI, Bangalore

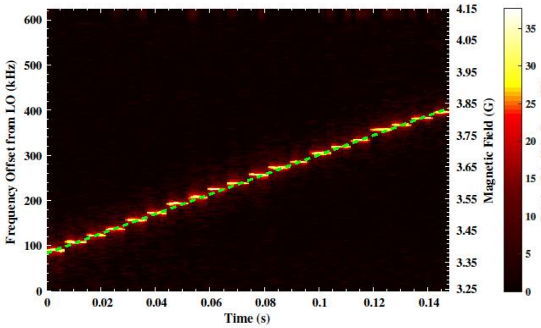
Also Lead Principal Investigator of National Quantum Mission Technology group on neutral atom and trapped ion based quantum computing hardware

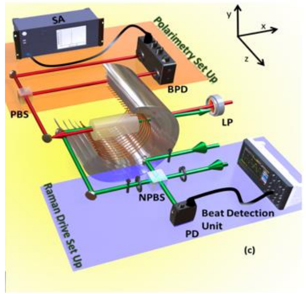


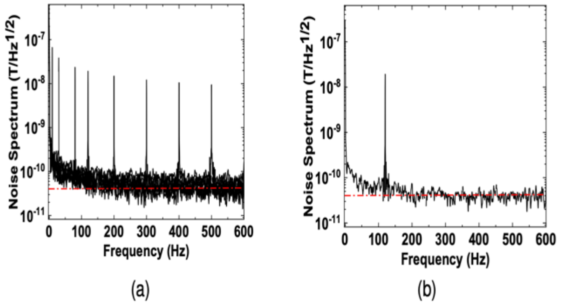












QuMiX Team and Funding Support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Gourab Pal, PhD
2025

I-HUB QUANTUM TECHNOLOGY FOUNDATION

I-HUB Quantum Technology Foundation

National Quantum Mission

DST@50 1971-2021 DEPARTMENT OF SCIENCE & TECHNOLOGY

MeitY Government of India

Relevant Publications, and Project highlights

National Quantum Mission

DST@ 1971-2021 विज्ञान एवं प्रौद्योगिकी विभाग DEPARTMENT OF SCIENCE & TECHNOLOGY

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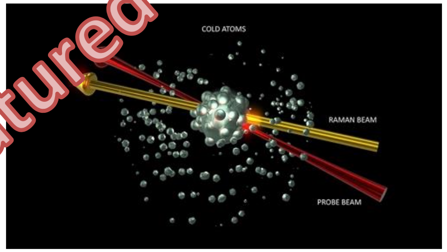
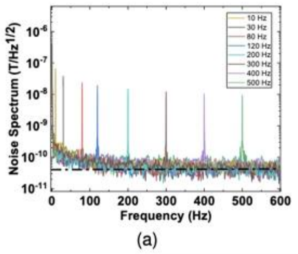
NATIONAL QUANTUM MISSION

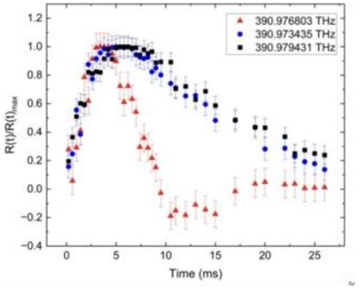
Featured



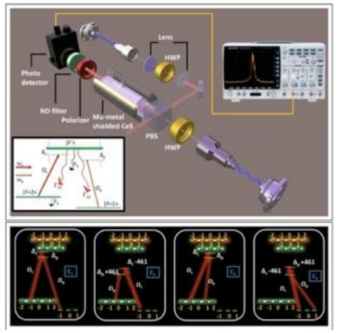
Appl Phys Lett, 127, 044004 (2025)



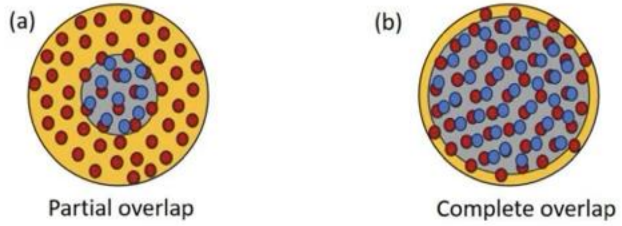
IEEE-TIM, vol. 74, 1-10, (2025)



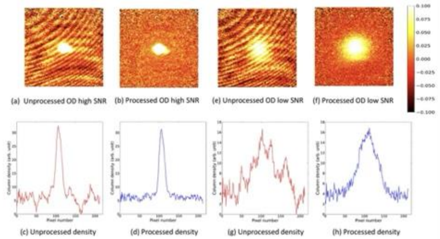
Optics Letters 49 (15), 4377 (2024)



Physica Scripta 99 (8), 085103 (2024)



Opt. Express 33, 22654-22665 (2025)



Applied Optics 62 (33), 8786 (2023)

Accompanying "Scilight" article by AIP publishing:

"Spin noise spectroscopy provides non-destructive view of cold atoms"


Applied Physics Letters ARTICLE pubs.aip.org/aip/apl

RESEARCH ARTICLE | JULY 31 2025

Real-time local density probe for cold atoms utilizing Raman driven spin noise spectroscopy

Sayari Majumder; Bhagyashri Bidwai; Bernadette Varsha; Saptarishi Chaudhuri

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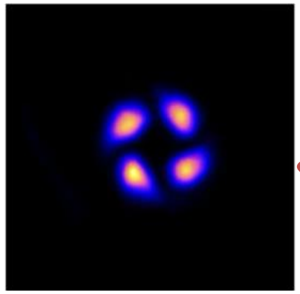
+ Author & Article Information

Appl. Phys. Lett. 127, 044004 (2025)

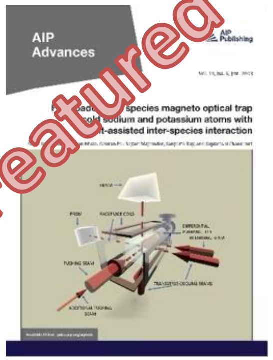
https://doi.org/10.1063/5.0277027 Article history

A fast detector of atomic qubits (micro-second) as opposed to present global state-of-the-art of 10s of milliseconds

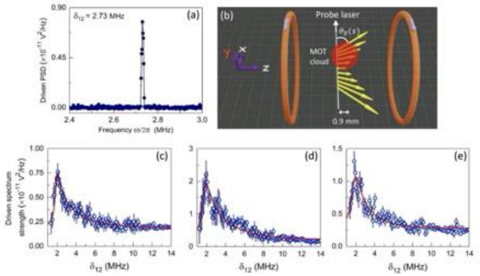


Springer-Nature J. Optics, 10.1007 (2024)

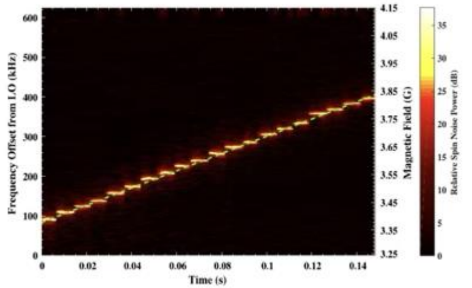
Featured



AIP Advances 13, 065317 (2023)



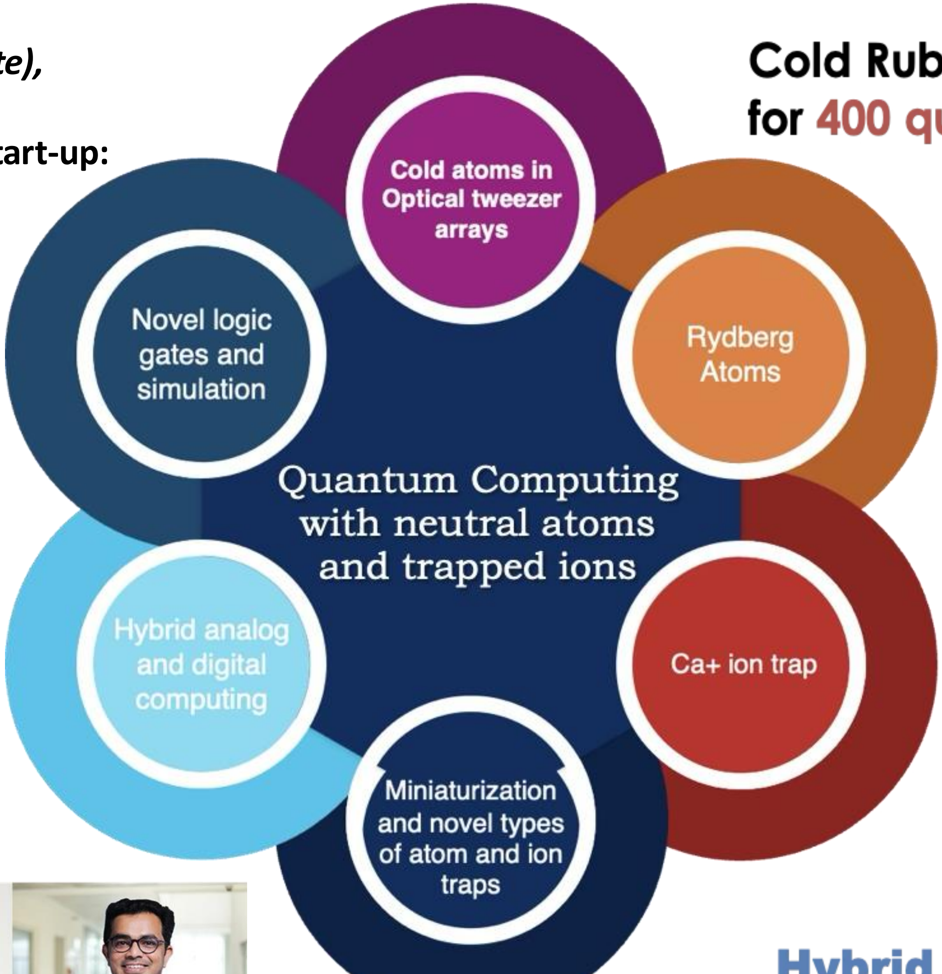
Phys Rev Res 3, 043171 (2021)



IEEE-TIM, ***70***, pp. 1-8, 2021

National Quantum Mission

7 institution, 8 PI consortium
(1 DST institute + 4 IIT s+ 1 IISER + 1 DAE institute),
Lead Inst: RRI (Saptarishi Chaudhuri)
Productization effort through RRI Lab spin-off Start-up:
RydCOMP (full stack quantum Computing solution provider)
Platform: anviQa
[Atom Network Versatile Integrated Quantum Architecture]



Cold Rubidium atoms in optical tweezer arrays for 400 qubit Quantum Computer

Highly excited Rydberg atoms for entanglement generation

Linear ion (Ca+) trap based 50 qubit Quantum Computer

Development on novel logic gate protocols and simulations using ions and atoms

Hybrid universal (analog and digital) computing platform

Saptarishi Chaudhuri

Umakant Rapol
IISER Pune

Ajay Wasan
IIT Roorkee

Ashok Mohapatra
NISER

Kanhaiya Pandey
IIT G

Ranjita Chanu
IIT Kanpur

Utpal Roy
IIT P

Rejish Nath
IISER Pune

Possible exploration of miniaturisation of atom and ion trap designs

Quantum Mixture Laboratory, RRI

- Cold gas Mixture: Simultaneous laser cooling and trapping of Sodium (Bosonic) and Potassium (Bosonic and Fermionic)
- Ultra-cold molecular spectroscopy
- Interaction induced modification of transport properties of cold atoms
- Spin noise spectroscopy (SNS) in cold and thermal atoms
- Quantum sensing and magnetometry using neutral atom spins
- Quantum processor (digital and analog) using cold Rubidium atoms in array of Optical tweezers, excited to high n Rydberg states
- Quantum Optics, Electromagnetically Induced Transparency
- Fast switching of Orbital Angular Momentum states of light.

Context, Challenges, Hardware and Peripherals

Quantum Technologies with ultra cold neutral atoms

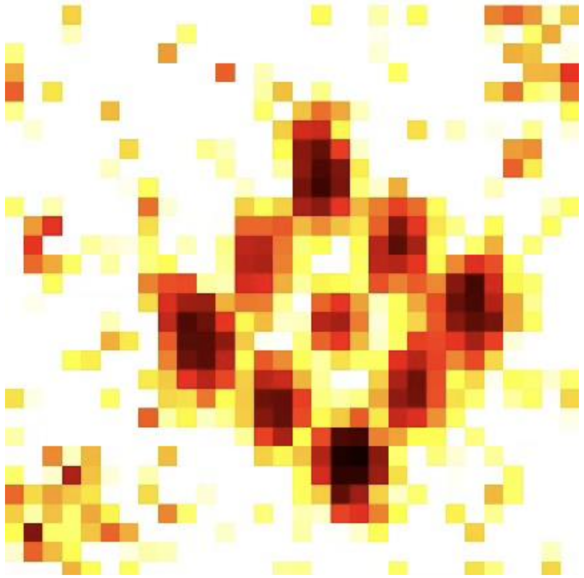
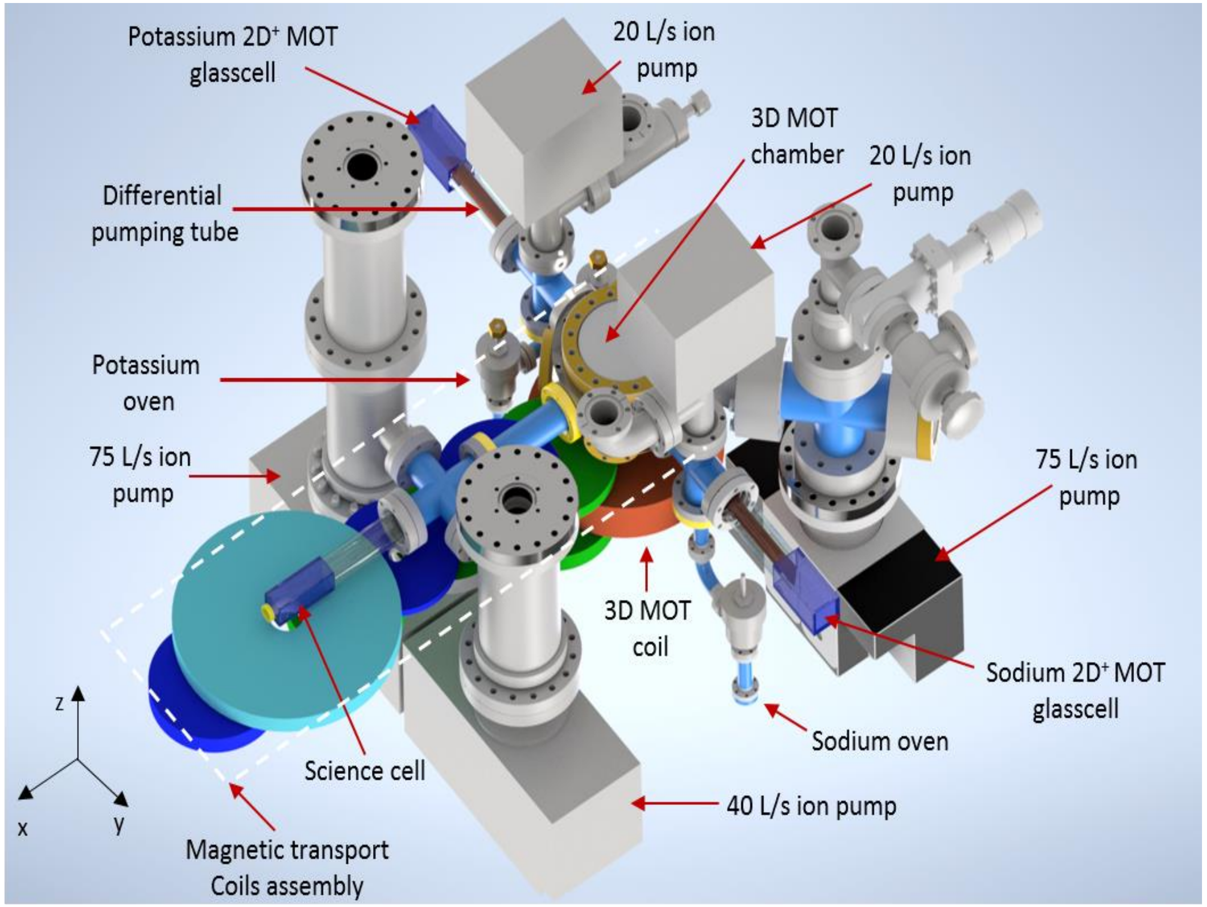


Image: array of cold atoms in Structured potential @RRI

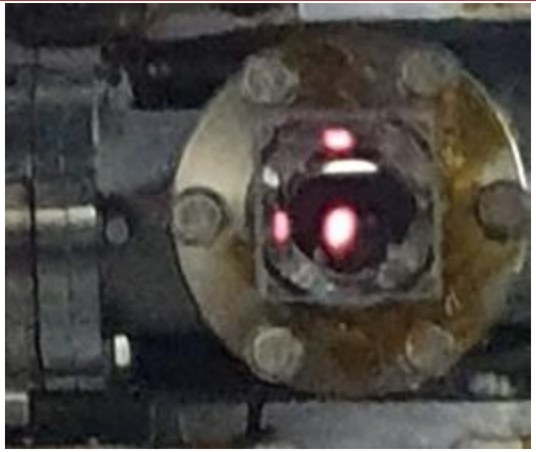
- Individual atoms / atom cluster (dark spots in left image) can act as Qubit and / or sensor (for magnetic / electric fields)
- Challenge is to detect / image them in real time and with high signal-to-noise ratio
- Traditional technology is to cool and trap atoms in ultra-high vacuum using laser light and collect scattered photons on CCD camera or absorption imaging
- Slow, noisy, instrumentation dependent
- Alternative detection techniques being worked on globally

In this talk: one such alternative technique – **Raman Driven Spin Noise Spectroscopy**

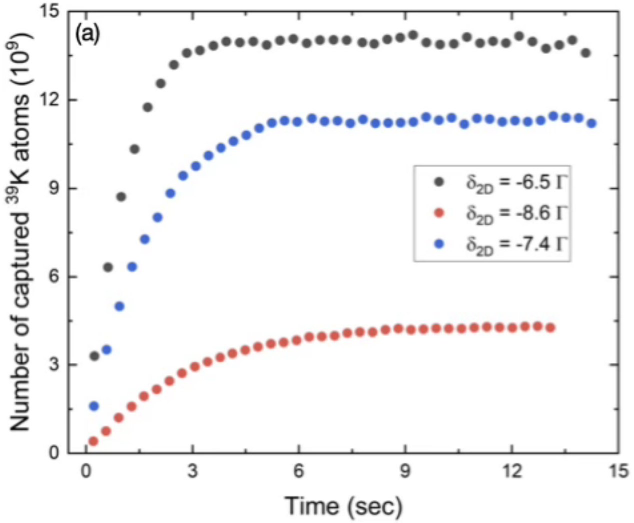
QuMiX Lab Experiment facilities

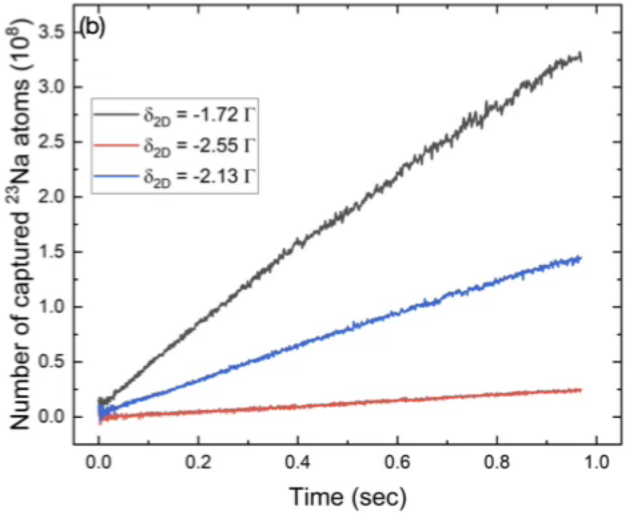


Sodium Atoms



Potassium Atoms

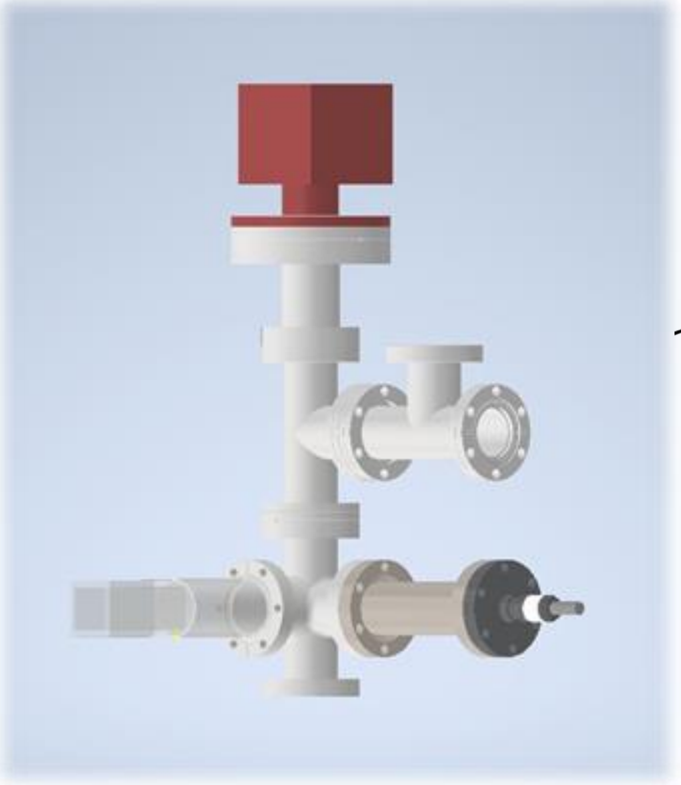




AIP Advances 13, 065317 (2023)

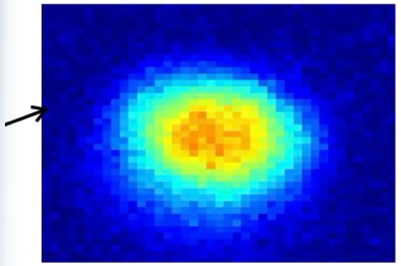
Simultaneous laser cooling and trapping of
^{39}K Atoms (3 x 10^{10}) and ^{23}Na Atoms (5.8 x 10^{8})
Using two 2 - dimensional magneto optical trap source
Optimized **magnetic transport**, **Optical dipole trapping**

QuMiX Lab Experiment facilities: Quantum computation with Rb

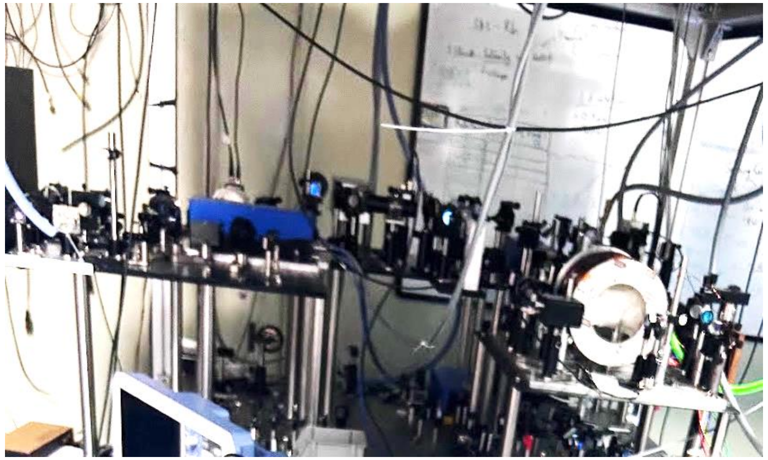


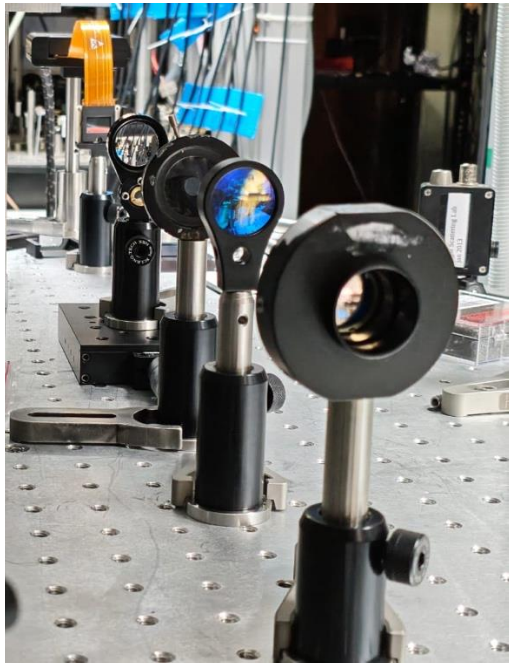
UHV system design

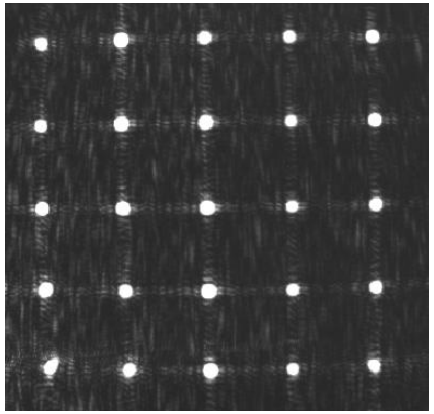
Laser systems



Fluorescence image of cold atomic cloud



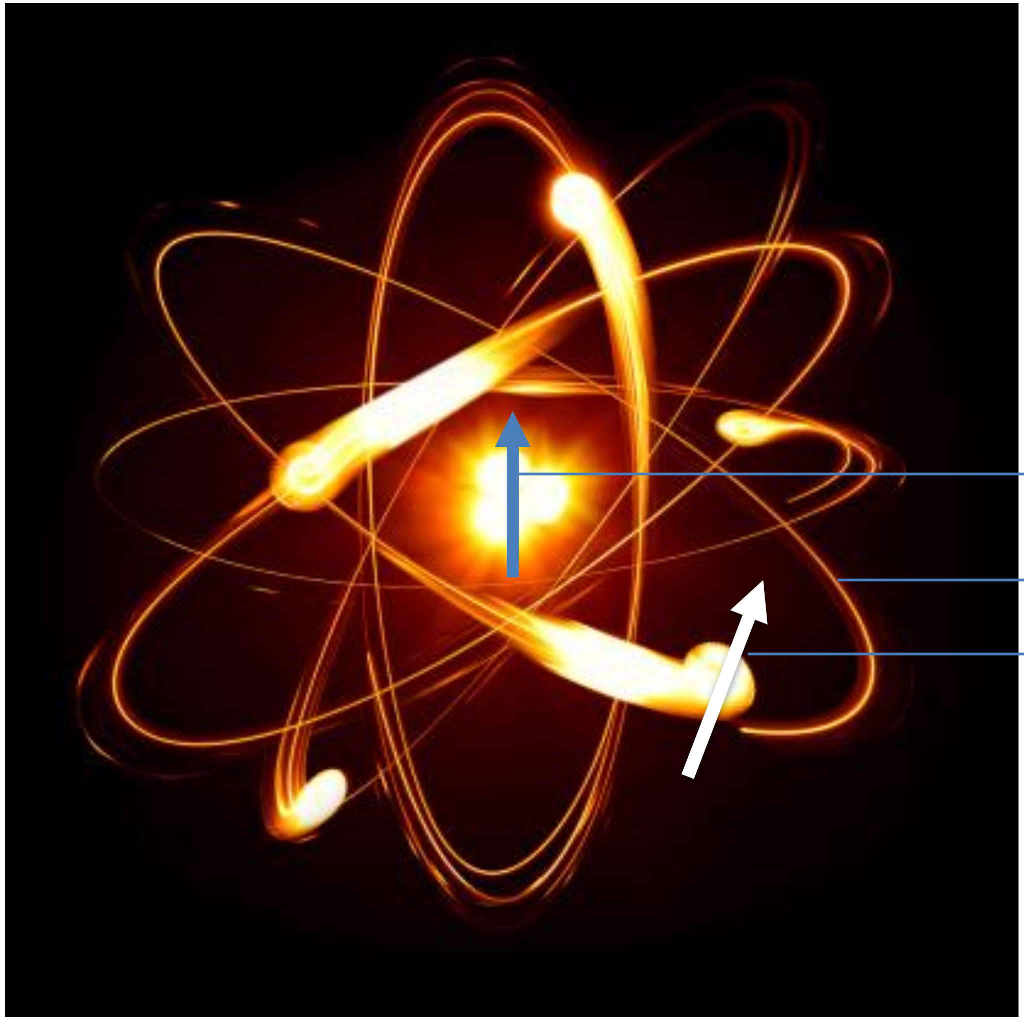




Spatial light modulator
And tweezer array

- 400 physical qubit neutral atom processor
- Defect free array Optimization
- Rydberg excitation via two photon (1013 nm + 420 nm) transition

Atomic Spin noise spectroscopy



Nuclear spin → **I**

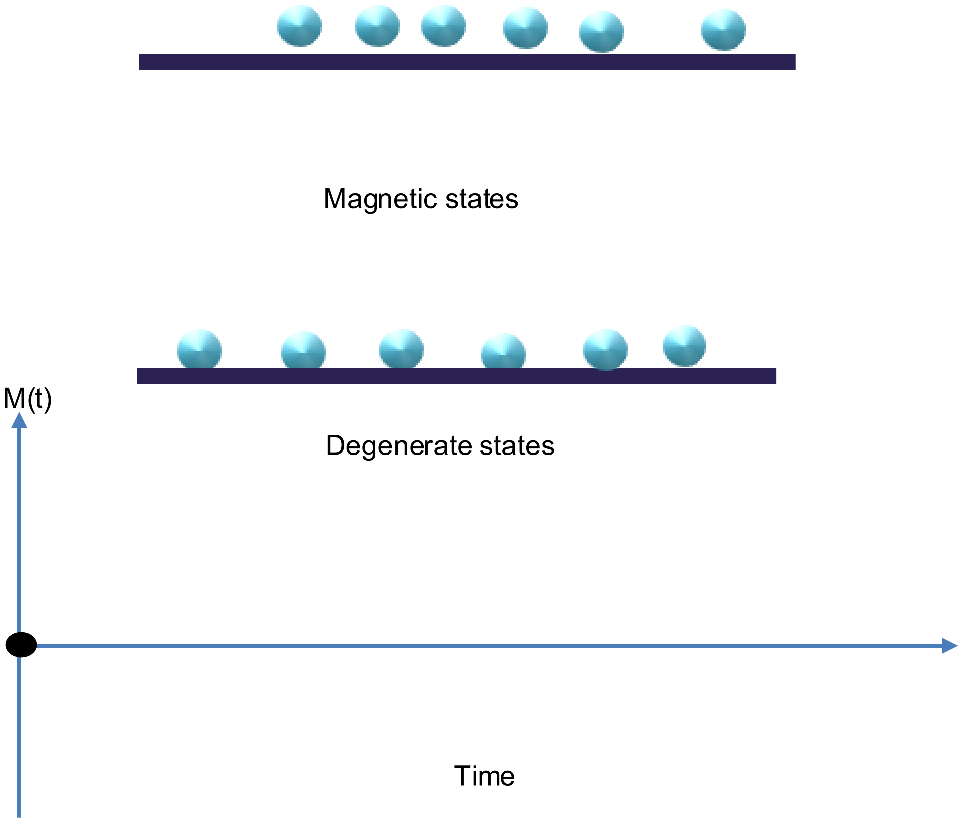
Orbital angular momentum, **L**

Electron spin →**S**

Electron angular Momentum, **J = L + S**
(Fine structure)

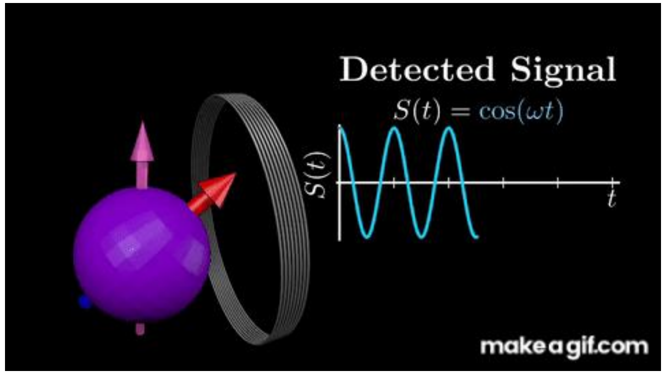
Total angular momentum, **F = I + J**
(Hyperfine structure)

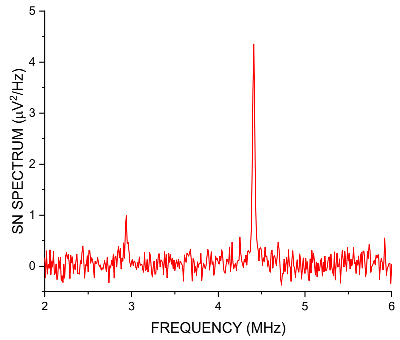
Detecting atomic Spin fluctuations



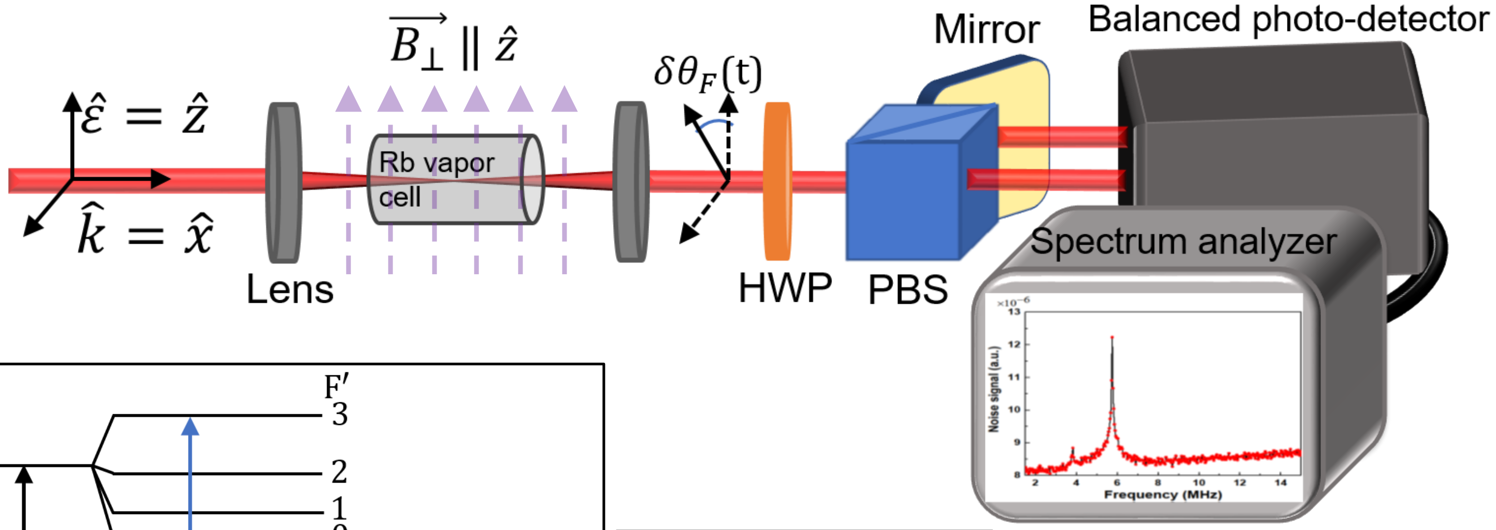
Spin noise arises from atomic magnetization fluctuation.

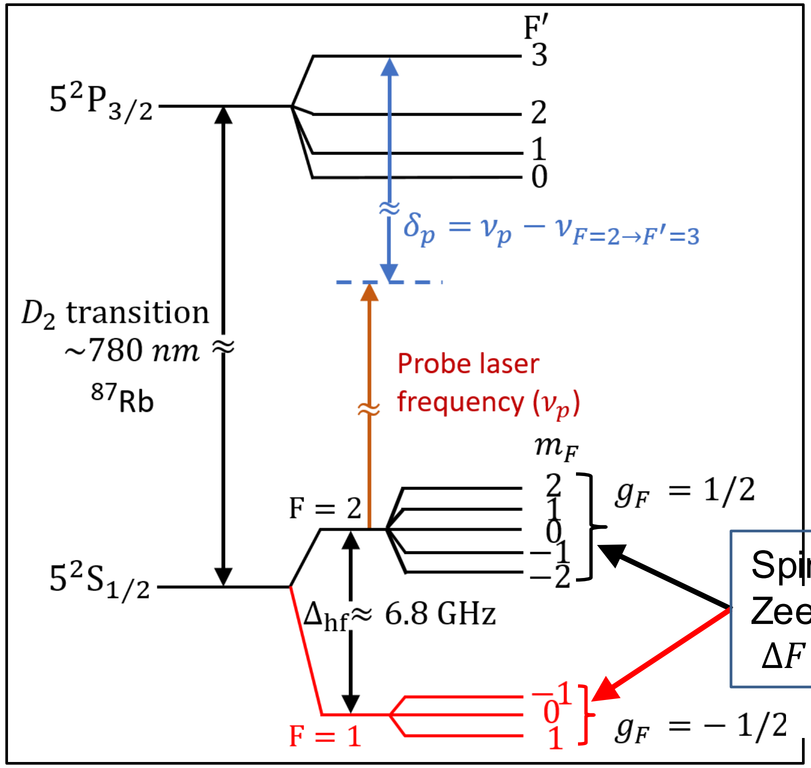
•SNS is described by the **fluctuation-dissipation theorem**.





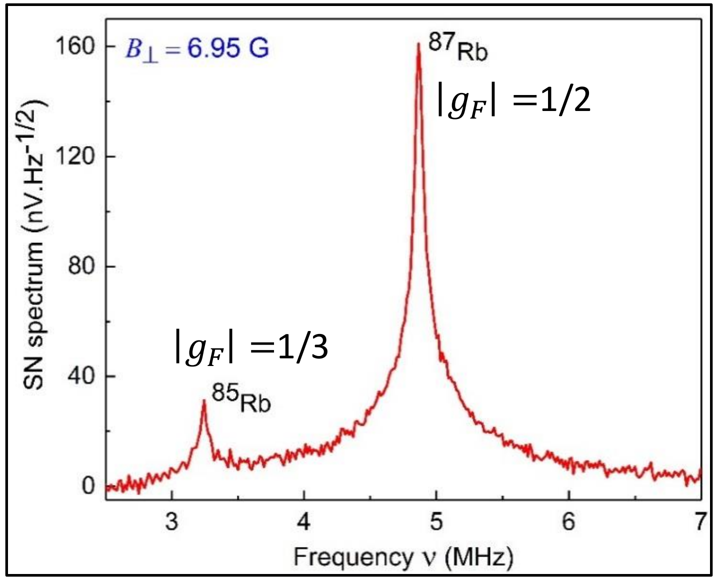
Intrinsic spin noise (SN) spectrum





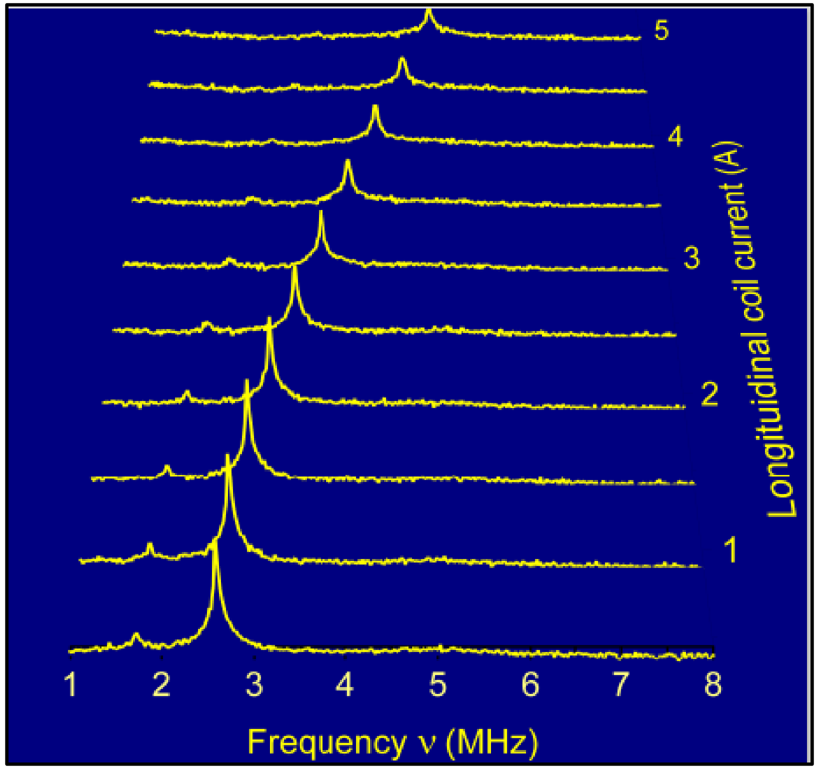
$$\Sigma = \int_0^\infty d\nu\, P(\nu) \propto \frac{I_p^2}{\delta_p^2}\left(\frac{n_0 l}{A}\right)$$

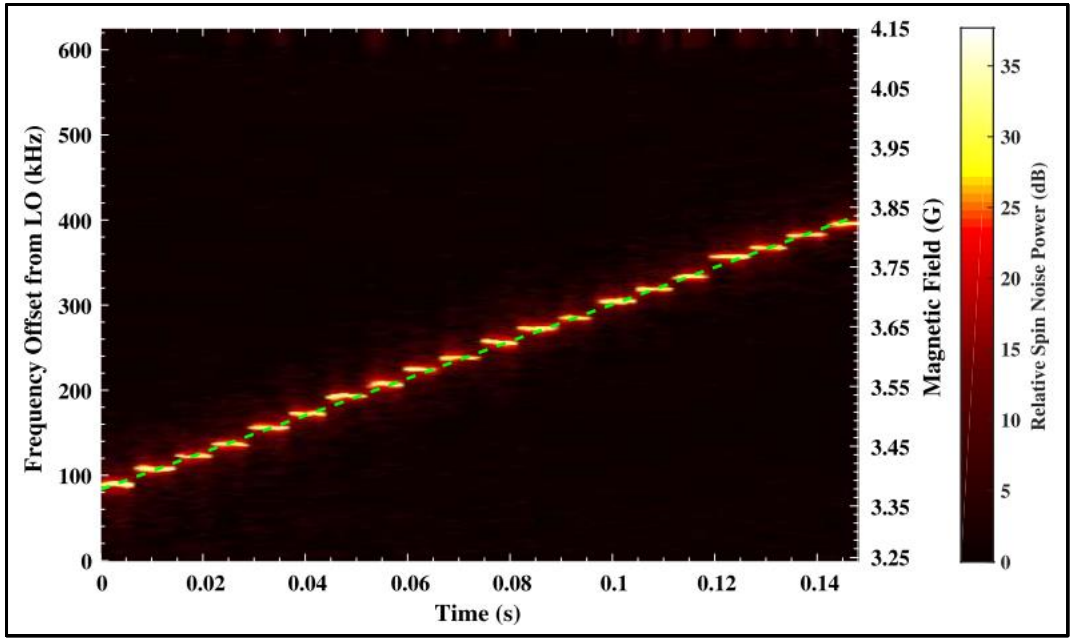
Spin fluctuations between Zeeman state
$\Delta F = 0, \Delta m_F = \pm 1$



Opt. Express 26, 32168 (2018).

Vector and time resolved magnetometry



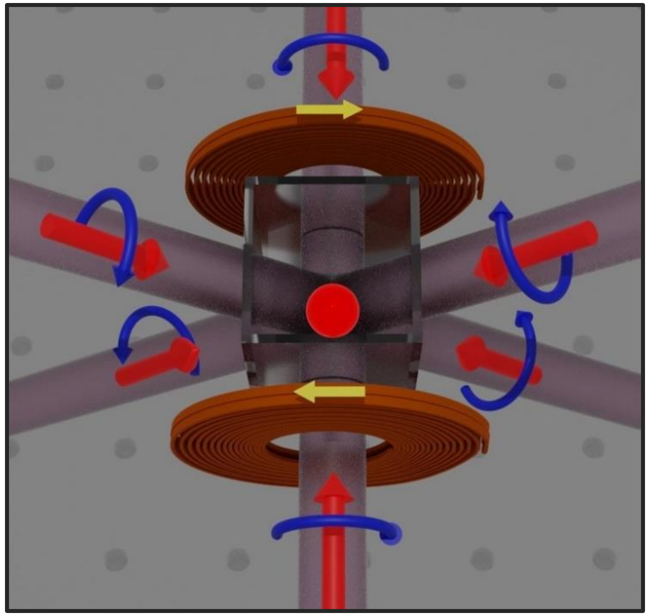


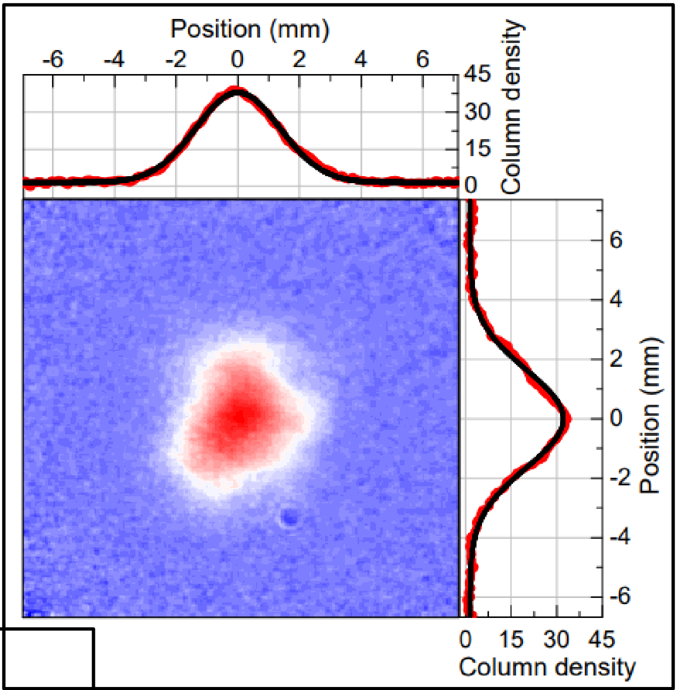
Local magnetic field direction changes spin noise spectrum both as a shift and line-shape change.

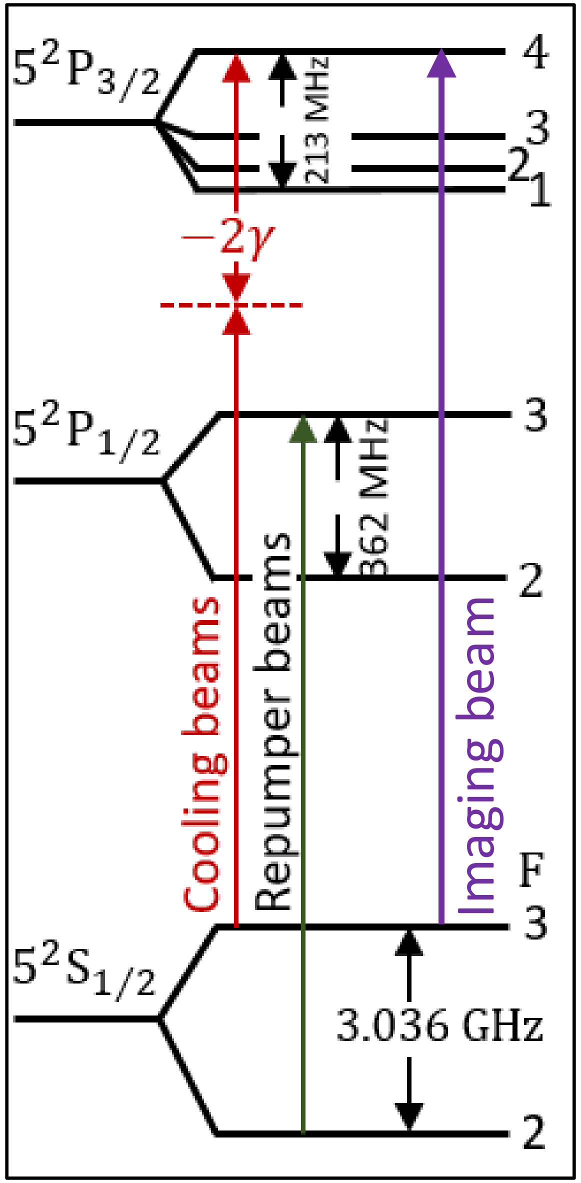
Our fast FPGA based detectors can resolve spin noise signal at ***m-sec*** time scale --- may be useful For ***sensing*** biological processes non-invasively

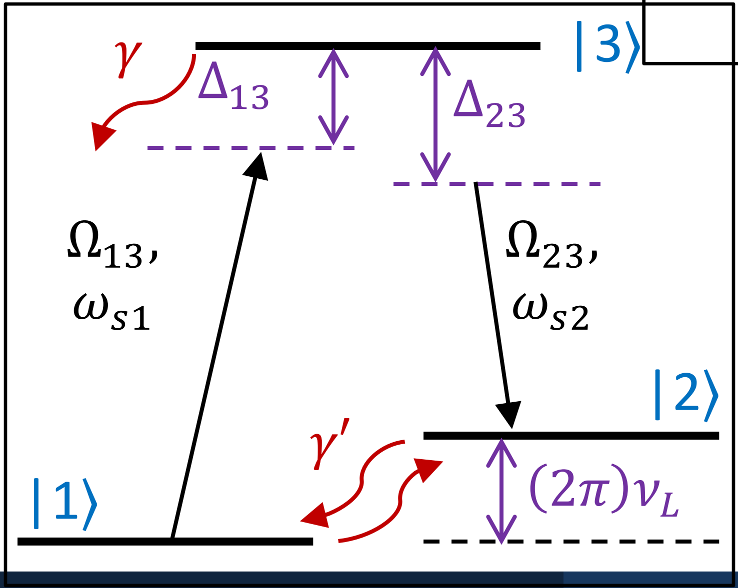
Ref: IEEE TIM, 2021

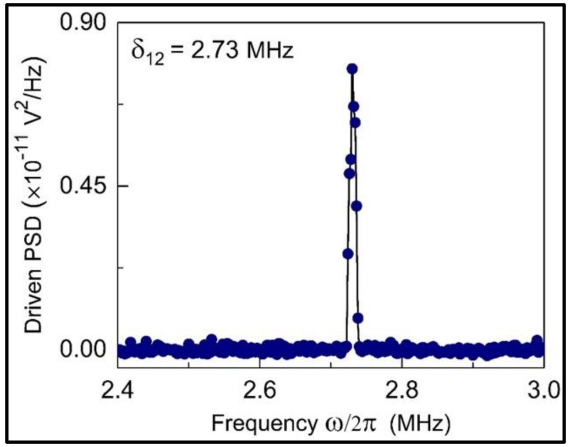
Direct “Raman Driven” spin fluctuation detection in cold atoms







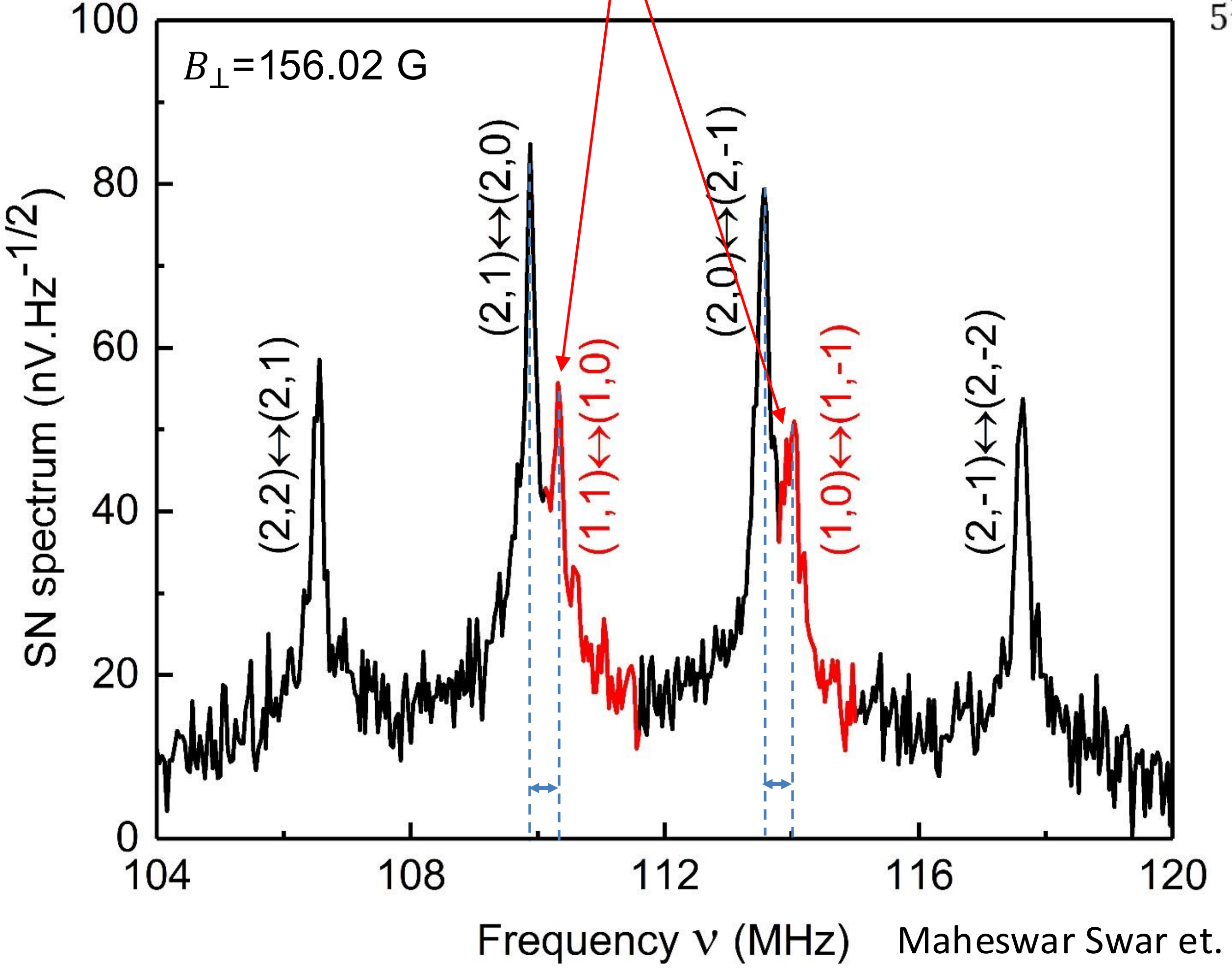




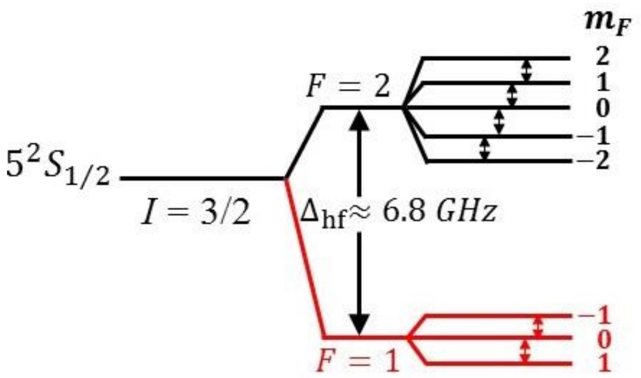
Phys. Rev. Res. (2021).

Hyperfine state detection using Spin Noise Spectroscopy

$$E_{F=I\pm\frac{1}{2},m_F} = -\frac{h\Delta_{\rm hf}}{2(2I+1)} + g_I\mu_B B_\perp m_F \pm \frac{h\Delta_{\rm hf}}{2}\sqrt{1+\frac{4m_F}{2I+1}x + x^2}$$



Maheswar Swar et. al. Optics Express **26** 32168 (2018)



SNS has potential in detecting the state F = 1 (say |0>) or F = 2 (say |1>) !

Will show a real time non-demolition detection later

Direct implication in Quantum Computing

Raman Driven Spin Noise Spectroscopy (RDSNS) as real time Atom density probe

Applied Physics Letters ARTICLE | pubs.aip.org/aip/apl

RESEARCH ARTICLE | JULY 31 2025

Real-time local density probe for cold atoms utilizing Raman driven spin noise spectroscopy

Sayari Majumder; Bhagyashri Bidwai; Bernadette Varsha; Saptarishi Chaudhuri

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+ Author & Article Information

Appl. Phys. Lett. 127, 044004 (2025)

https://doi.org/10.1063/5.0277027 Article history

Appl. Phys. Lett., Featured Article and Editor's Pick!

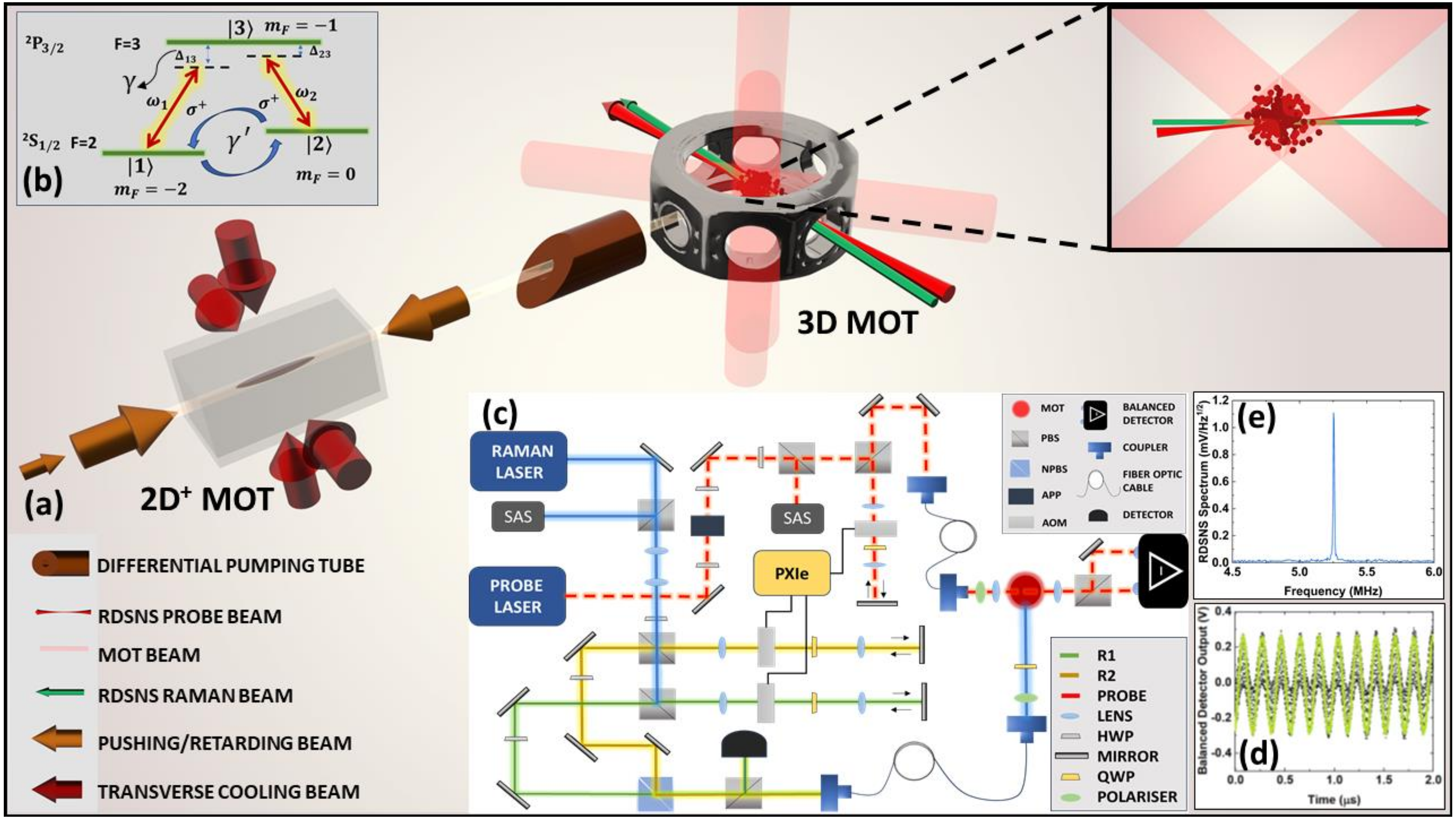
RESEARCH ARTICLE | JUNE 08 2023

Fast loaded dual species magneto optical trap of cold sodium and potassium atoms with light-assisted inter-species interaction

Sagar Sutradhar; Anirban Misra; Gourab Pal; Sayari Majumder; Sanjukta Roy; Saptarishi Chaudhuri

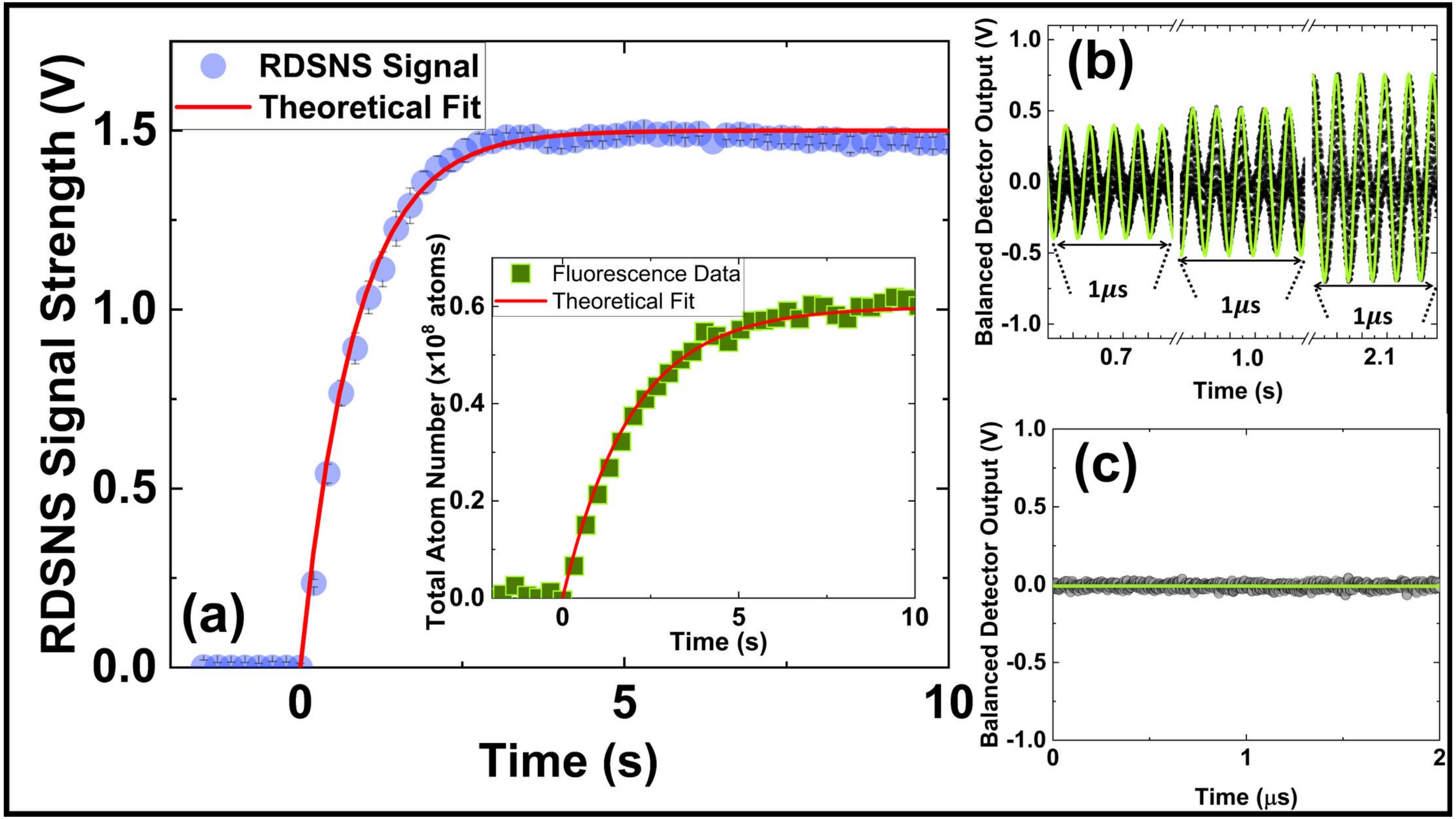
AIP Advances Featured article and Journal cover!

RDSNS as real time Atom density probe



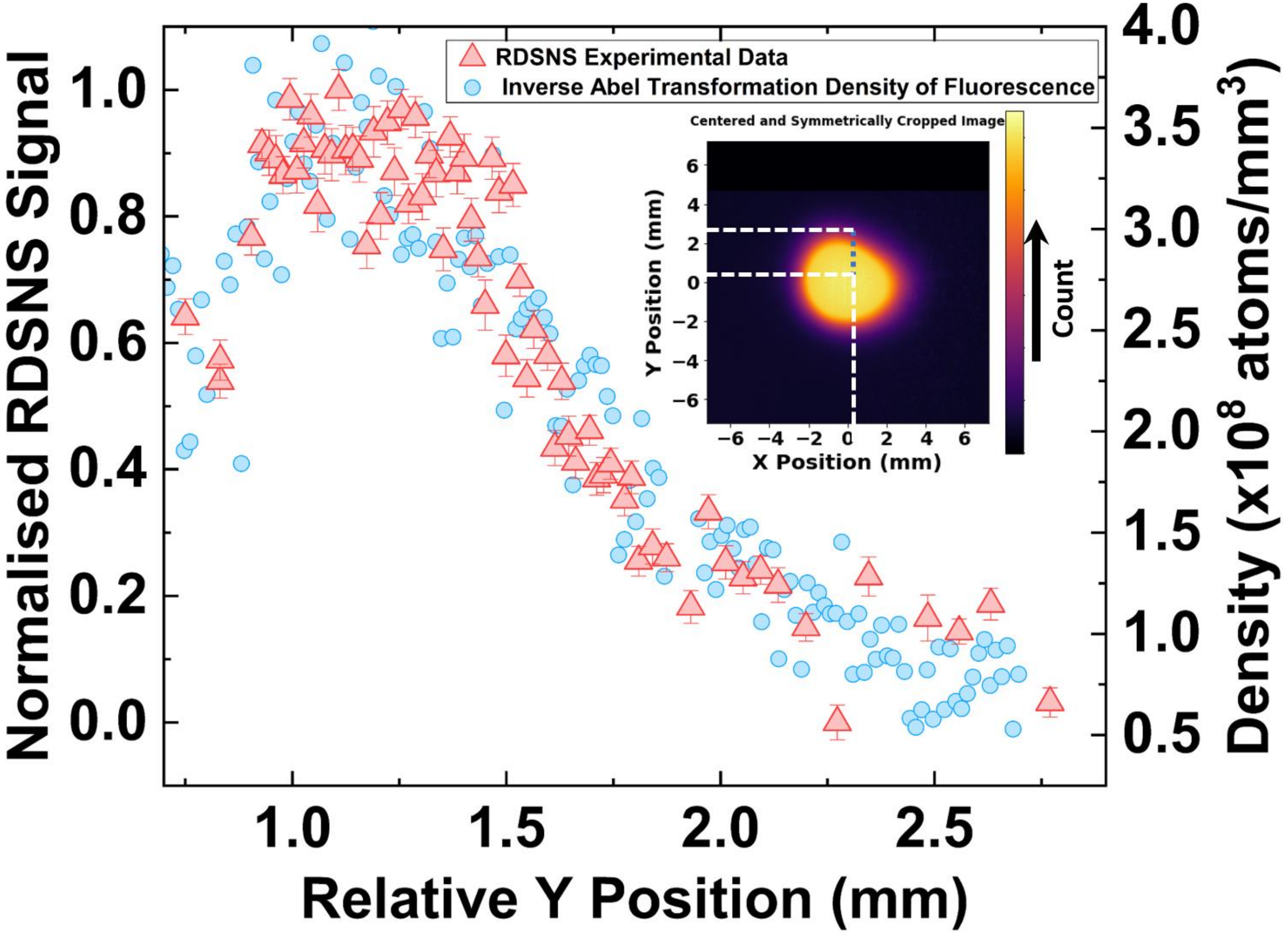
Appl. Phys. Lett. Vol 127 (2025)

RDSNS as real time Atom density probe



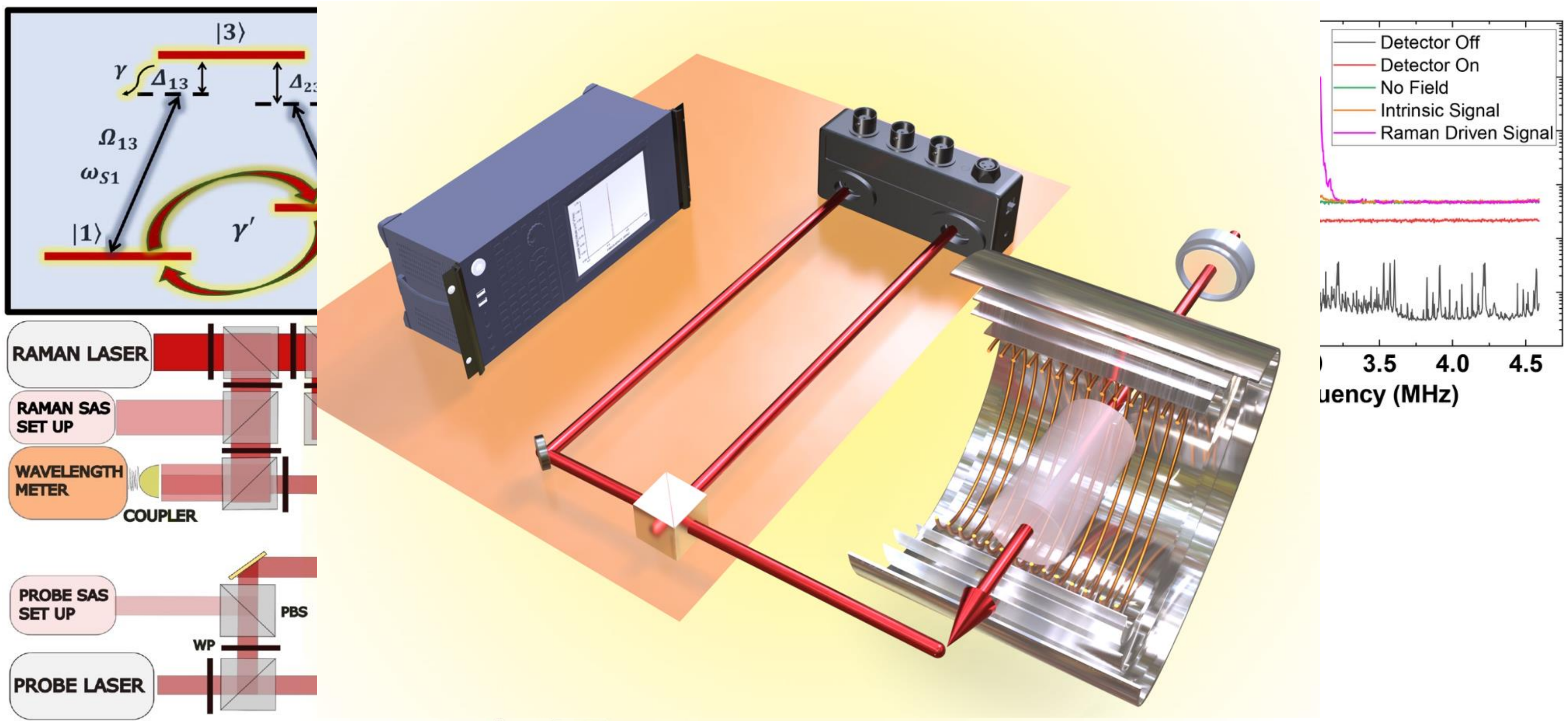
Appl. Phys. Lett. Vol 127 (2025)

RDSNS as real time Atom density probe



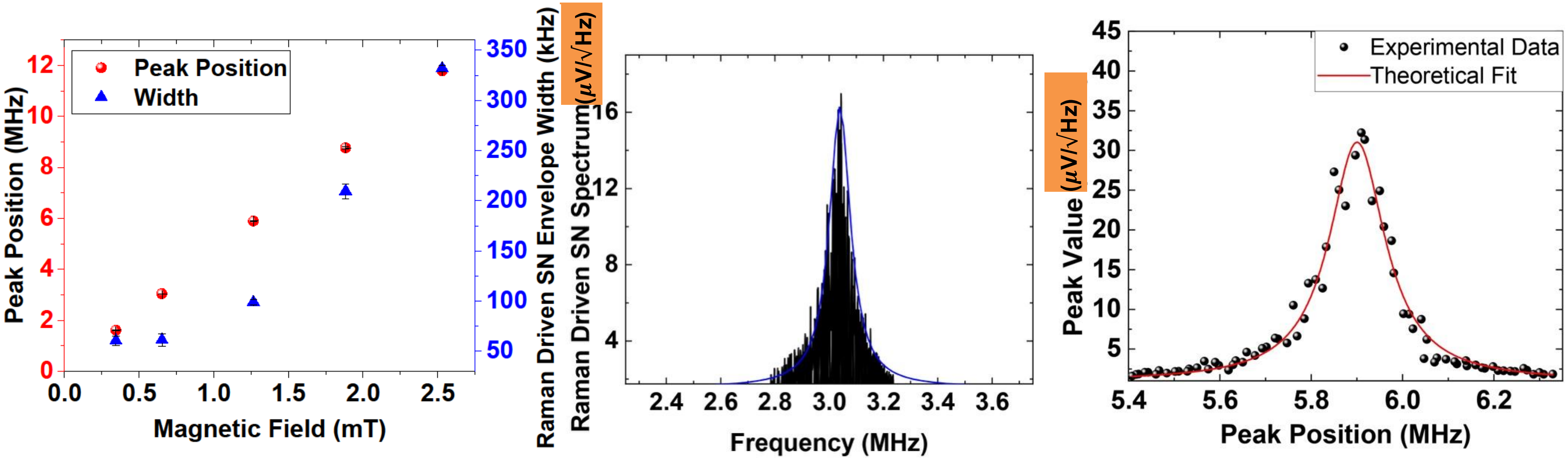
Appl. Phys. Lett. Vol 127 (2025)

RDSNS as Quantum sensor: Magnetometer operation



IEEE Transactions on Instrumentation and Measurement, vol. 74, pp. 1-10, 2025

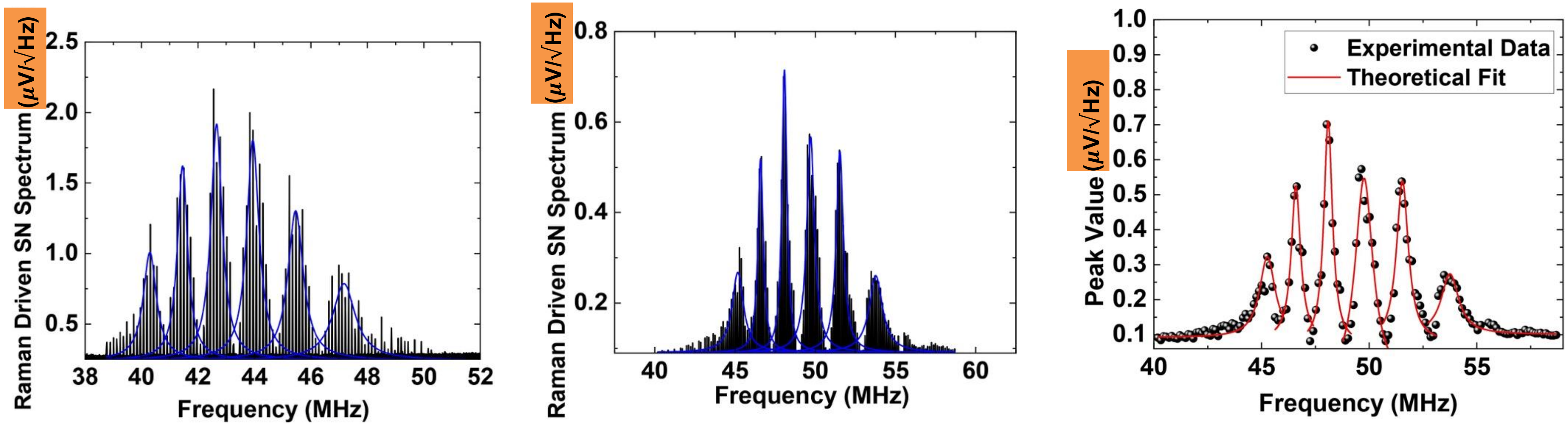
Low Field



❖ Raman Driven SNS signal as a function of external magnetic field.

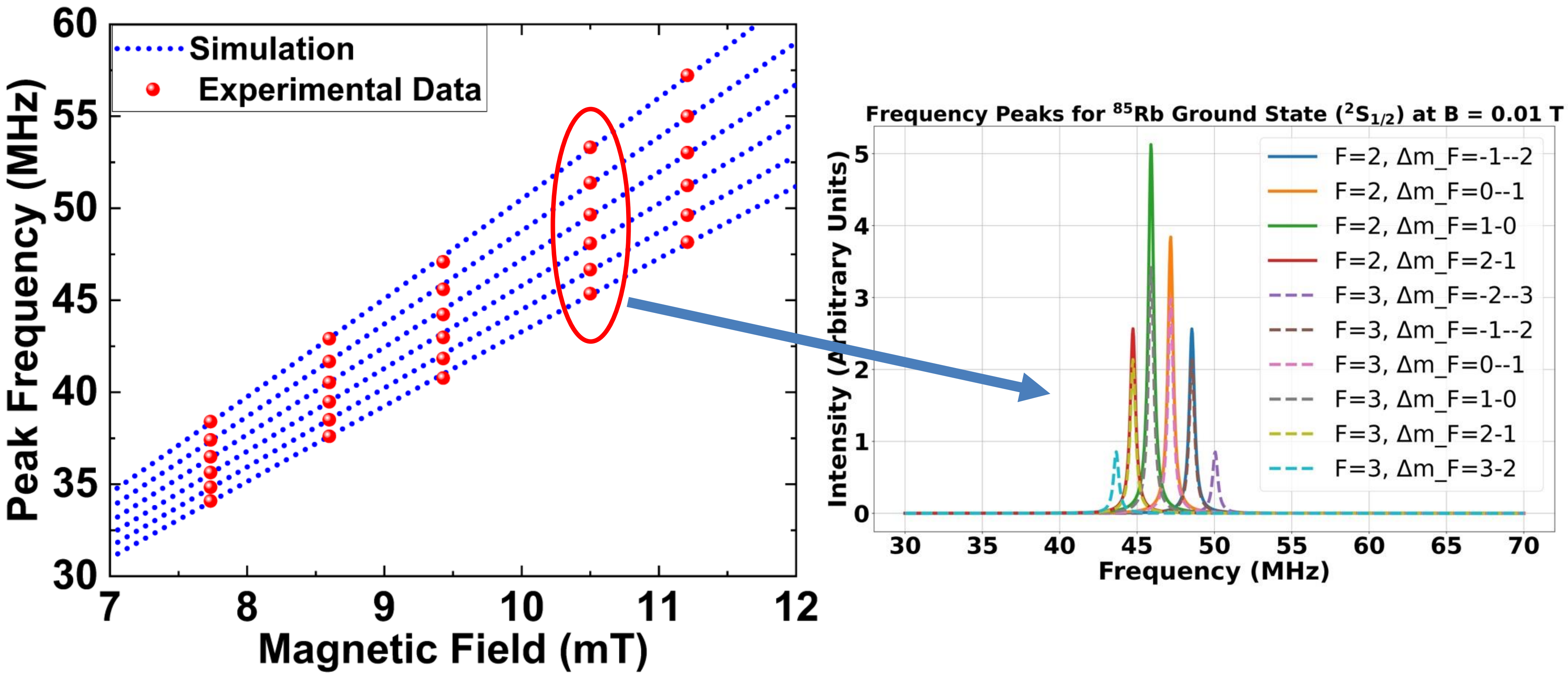
IEEE Transactions on Instrumentation and Measurement, vol. 74, pp. 1-10, 2025

High Field Experimental Data



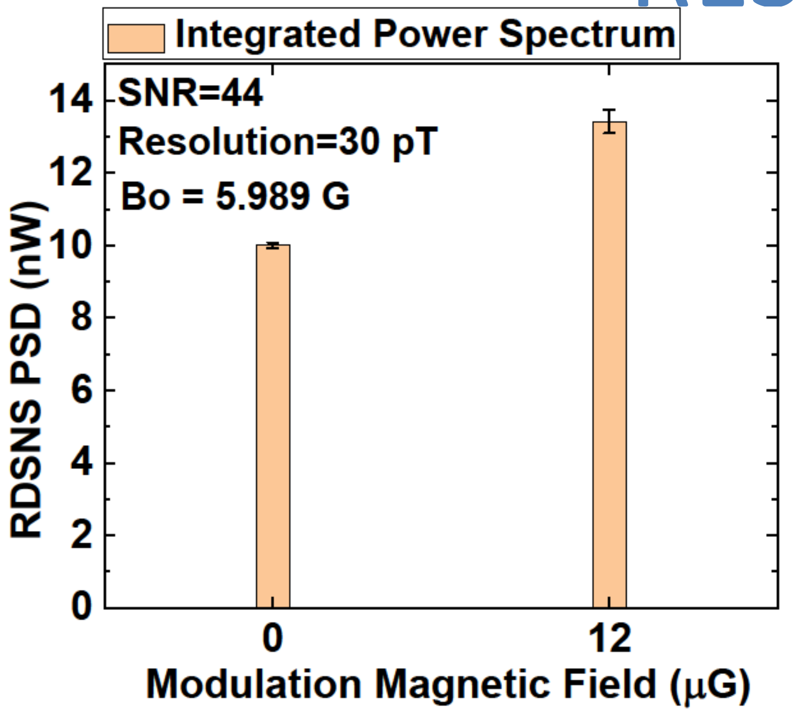
IEEE Transactions on Instrumentation and Measurement, vol. 74, pp. 1-10, 2025

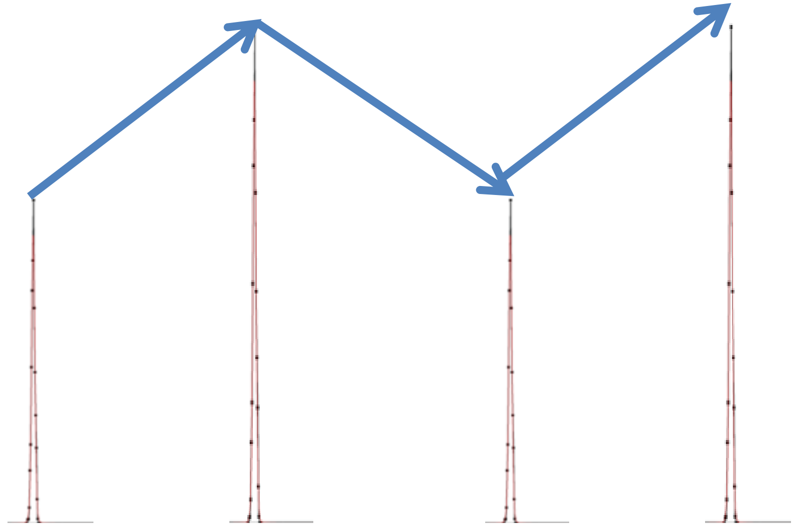
High Field Verification



IEEE Transactions on Instrumentation and Measurement, vol. 74, pp. 1-10, 2025

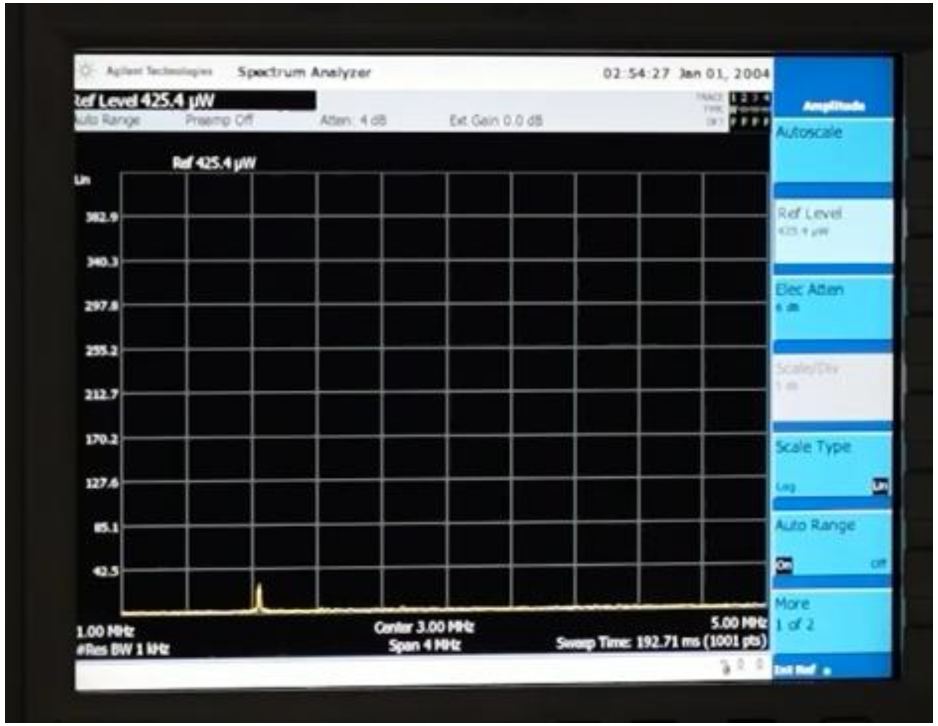
DC FIELD RESOLUTION





IEEE Transactions on Instrumentation and Measurement, vol. 74, pp. 1-10, 2025

AC MAGNETIC FIELD RESPONSE



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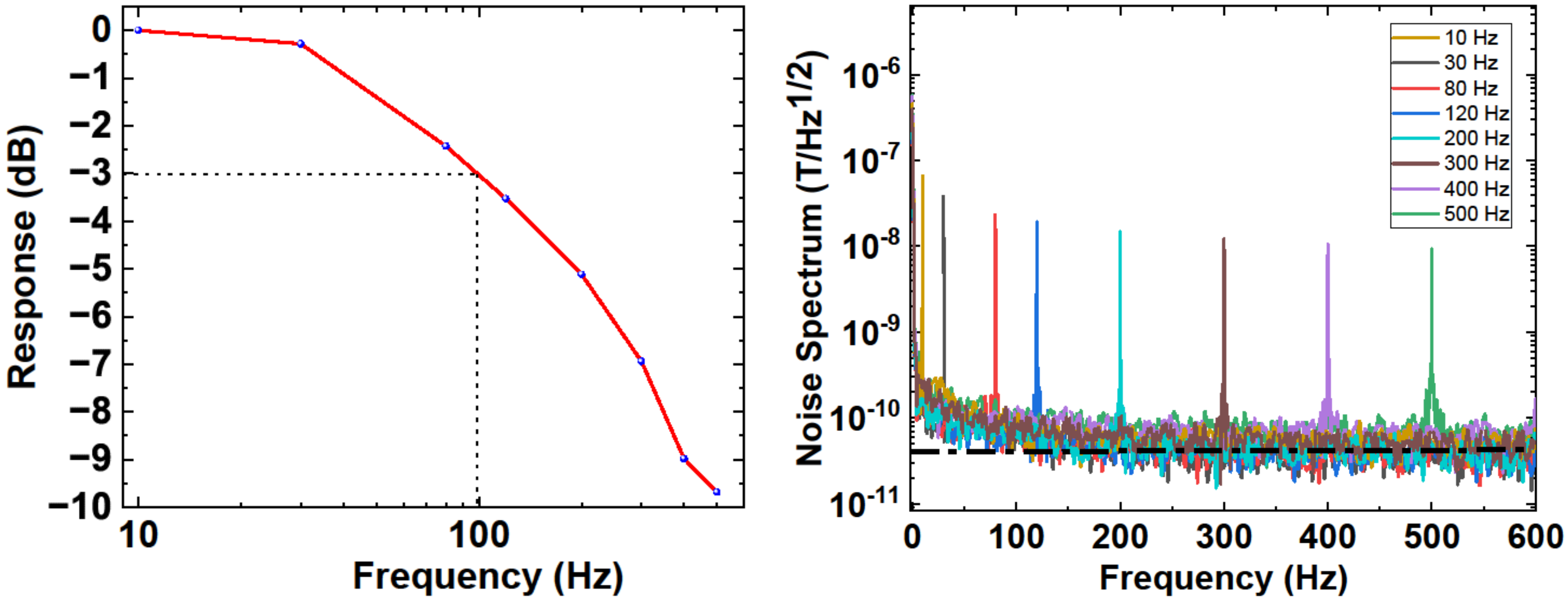
AC MAGNETOMETRY



Sensitivity = 30 pT/$\sqrt{Hz}$

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Conclusion and outlook

•SNS

•SNS enables sensitive measurements of spin dynamics without requiring active manipulation of the system, unlike optically pumped methods.

•SNS AS A MAGNETOMETER

•Use in atomic magnetometers for detecting ultra-weak magnetic fields in shielding free environment.

•SNS IN COLD ATOMS

•Potential for using as fast and high SNR atom counter and studying quantum effects like inter-species coherence

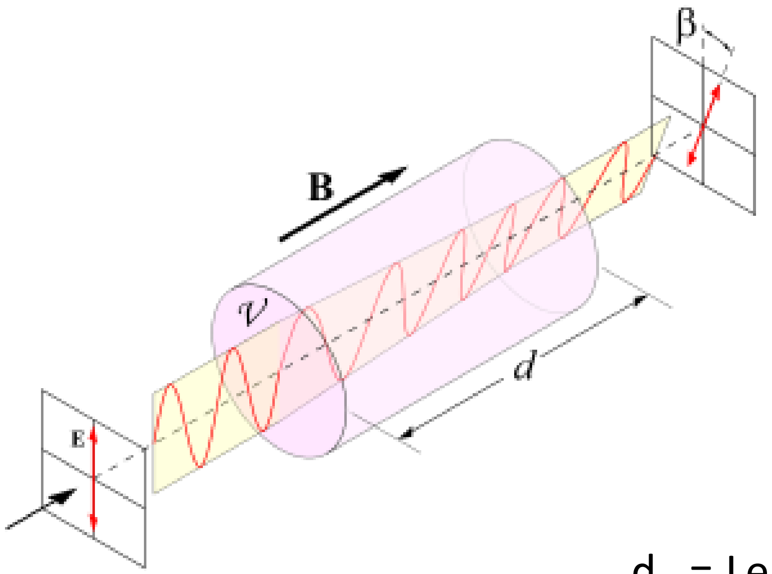
Extra slides

Principle of Operation:

How atomic ***magnetometers*** work?

By measuring Faraday rotation of probe light passing through atomic ensemble

Experimental technique: Faraday rotation

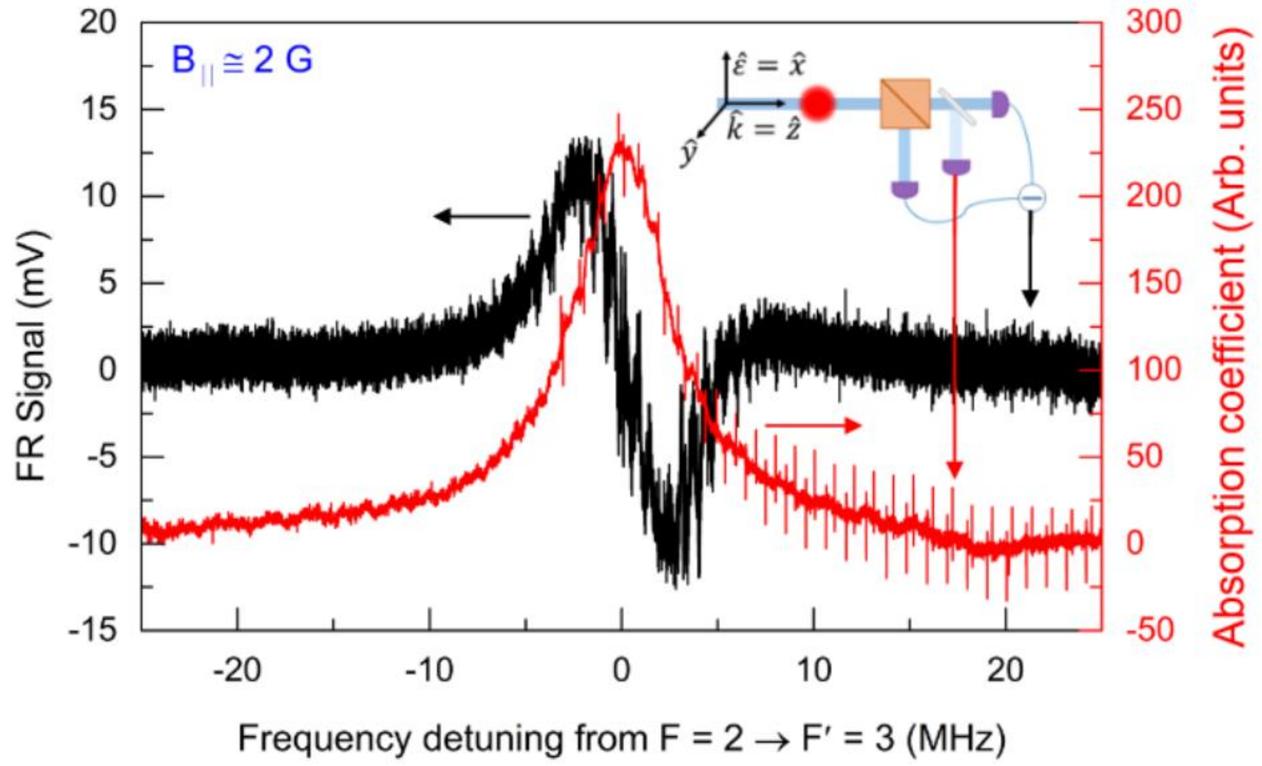


$$\beta = \nu d B$$

ν = Verdet constant
d = Length of material (atom cloud)
B = External magnetic field (the one to measure)

Image source: Wikipedia

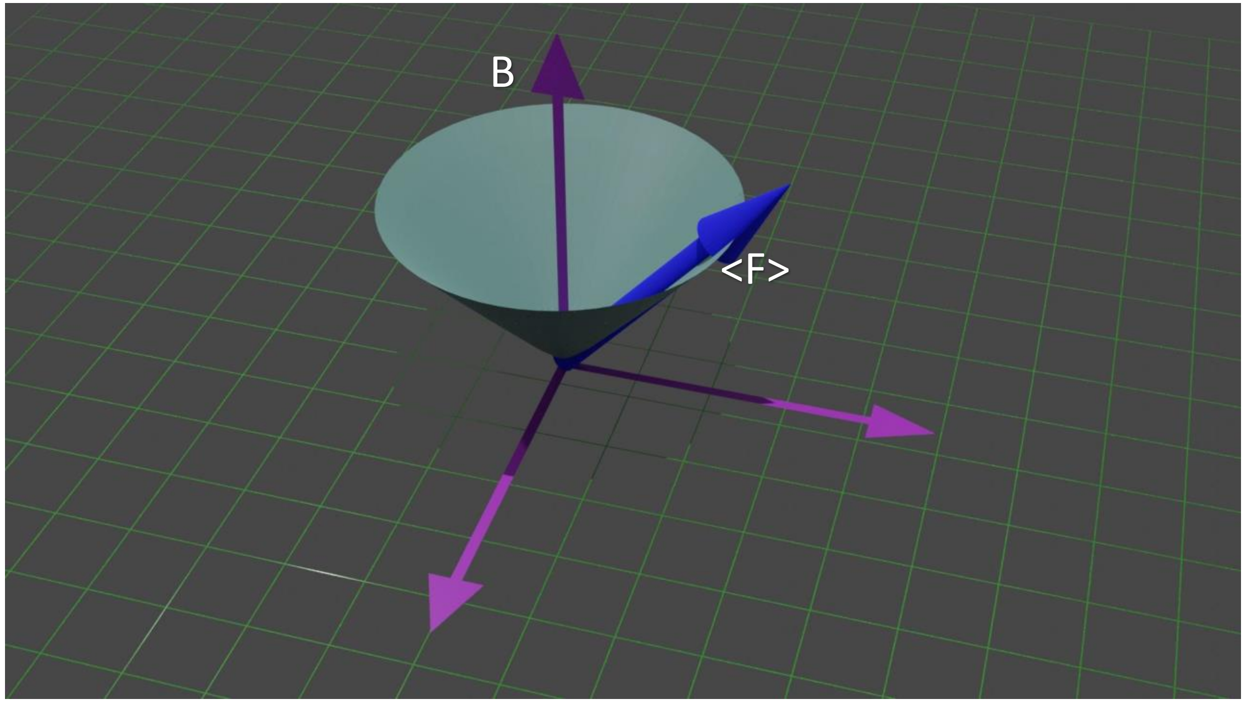
Faraday rotation from cold atoms



Data @RRI, unpublished

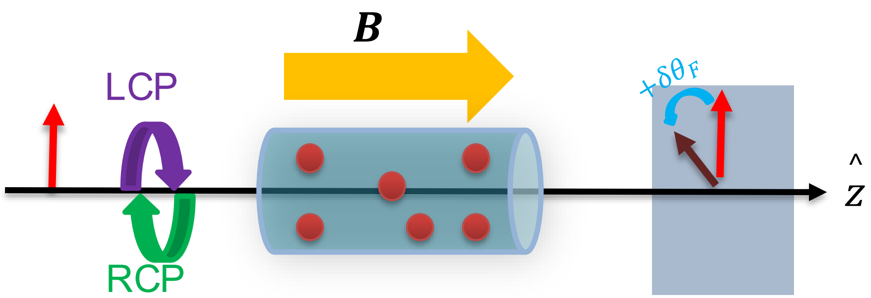
Concept of Larmor precession

Larmor precession of atomic spins in external magnetic field



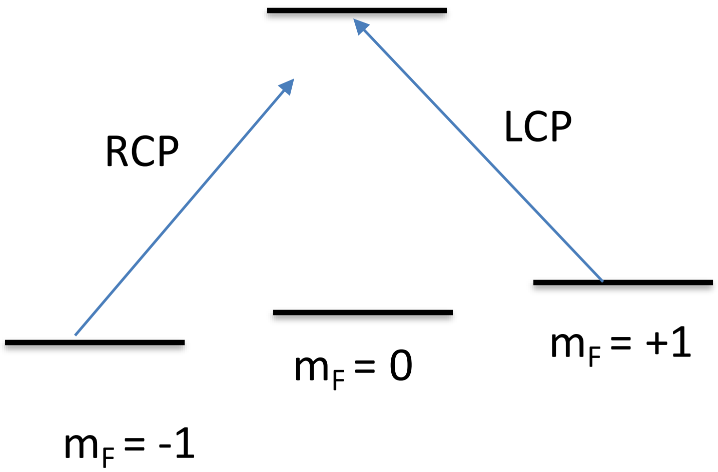
B : External magnetic field (Quantization axis)
<F>: atomic spin projection vector

An atomic physicist's explanation



LCP, RCP = Left / right circularly Polarized light

can be mapped to σ+ / σ- states Of light with correct quantization axis identification

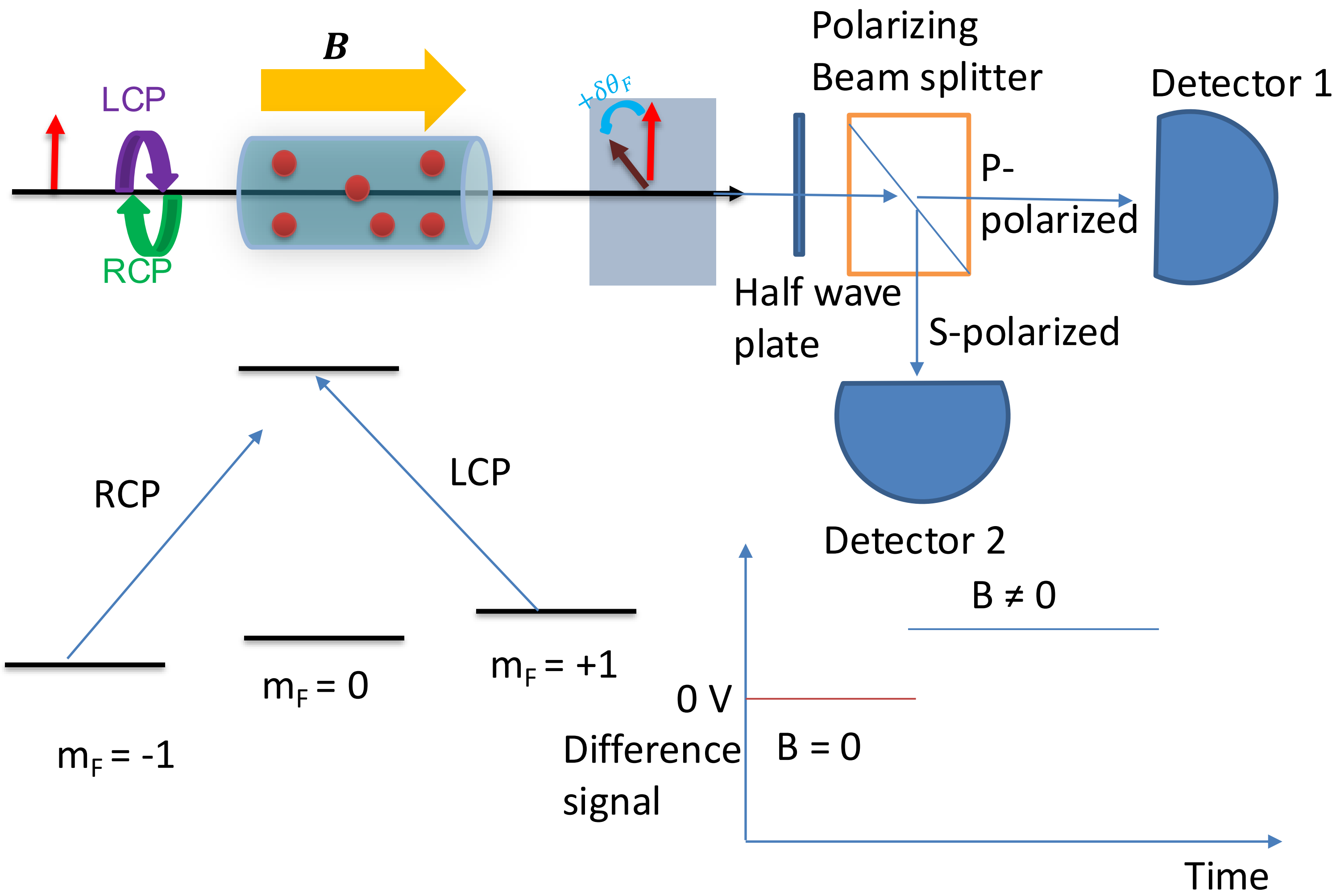


1) Depending on frequency of the laser w.r.t atomic transition →

2) different phase shift of LCP / RCP light →

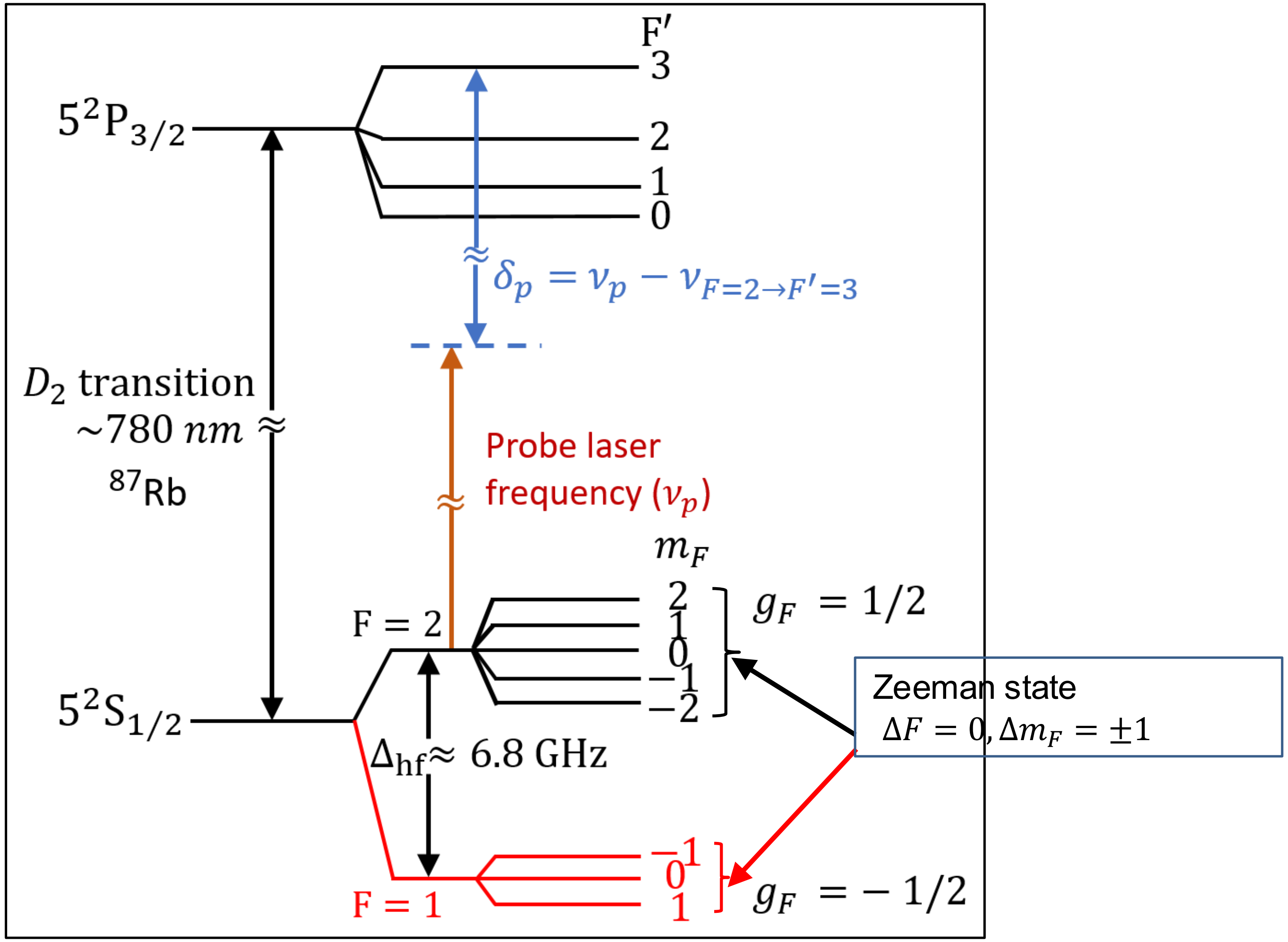
3) resultant outcoupled light polarization vector rotates by a angle w.r.t input polarization

An atomic physicist's explanation

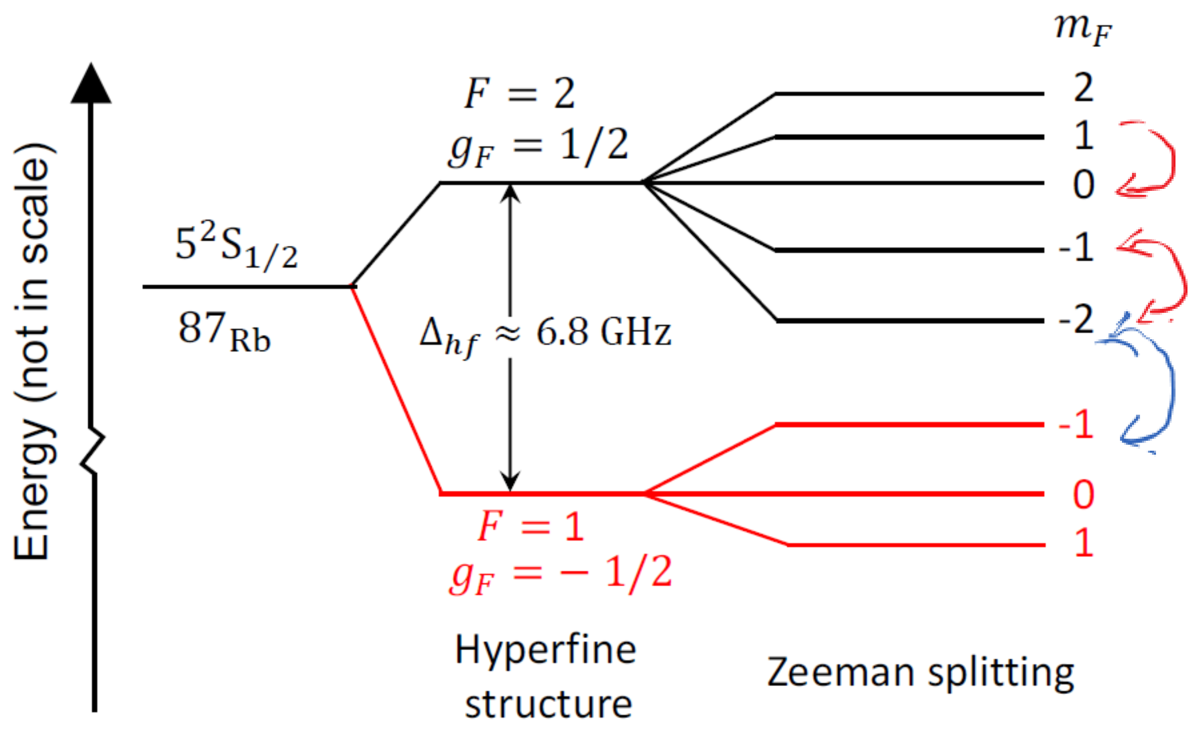


What is "Spin" in atoms

Example : Rubidium atoms (our test bed for some of the experiments)



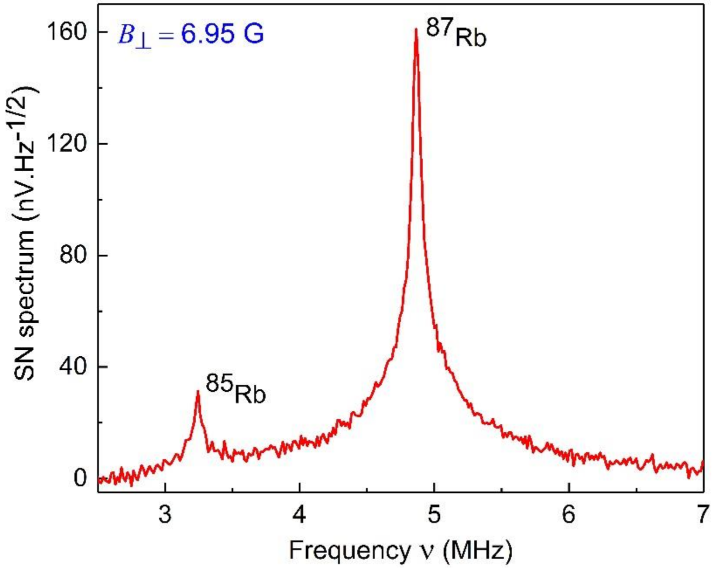
What is atomic Spin fluctuations

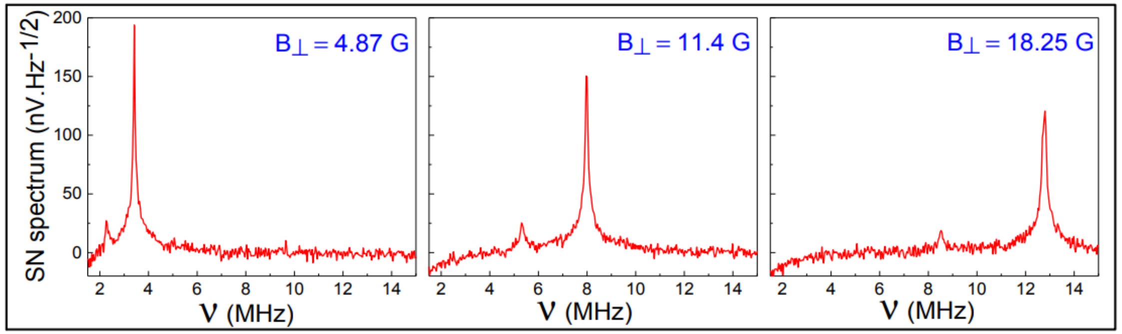


Population fluctuation between Zeeman levels

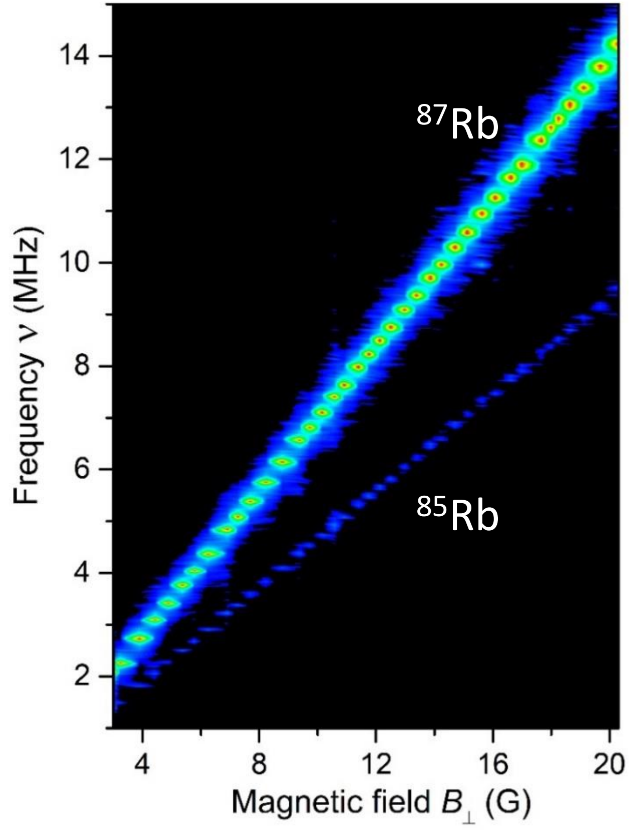
Reasons – 1) Thermal bath coupling, 2) Quantum fluctuations, 3) spin exchange collisions ….

Linear Zeeman regime (Low field measurements)





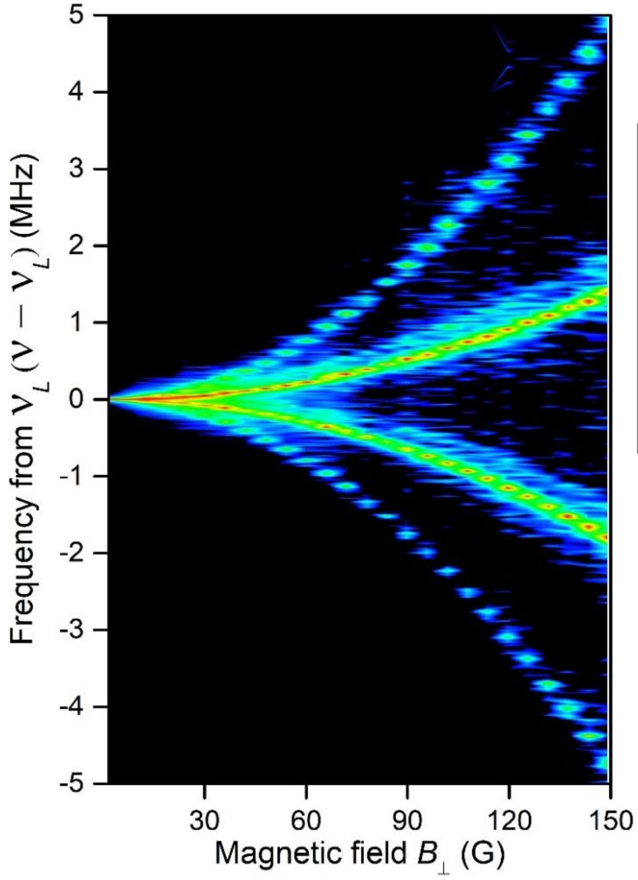
$$|g_F| = \frac{h\nu_L}{\mu_B B_\perp}$$



Parameters	Extracted value
$\|g_F\|$ (^{87}Rb)	0.500 (1)
$\|g_F\|$ (^{85}Rb)	0.333 (1)
Spin coherence rate	$\sim 3 \times 10^5\ s^{-1}$
$n_{87_{Rb}}$: $n_{85_{Rb}}$(T = 100ºC)	≈ 11 : 1

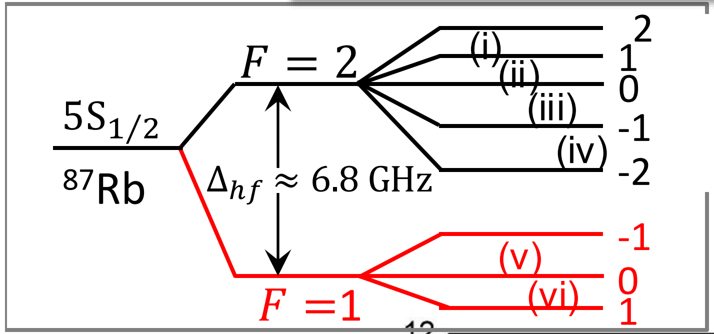
Opt. Express 26, 32168 (2018).

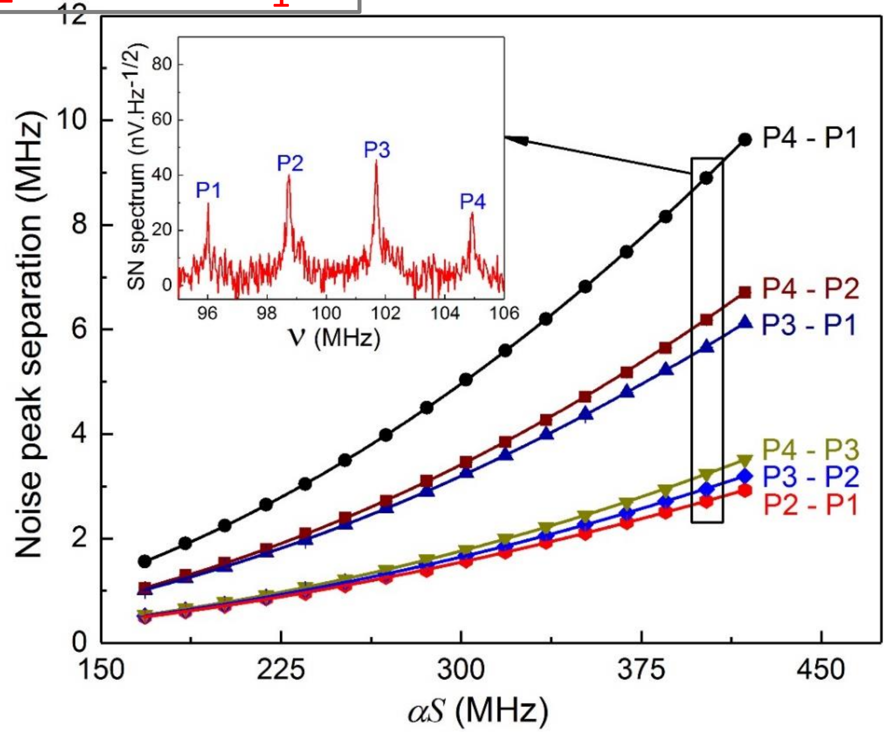
non-linear Zeeman regime (High field!)



$$E_{F=I\pm\frac{1}{2},m_F} = -\frac{h\Delta_{hf}}{2(2I+1)} + g_I\mu_B B_\perp m_F \pm \frac{h\Delta_{hf}}{2}\sqrt{1+\frac{4m_F}{2I+1}x + x^2}$$

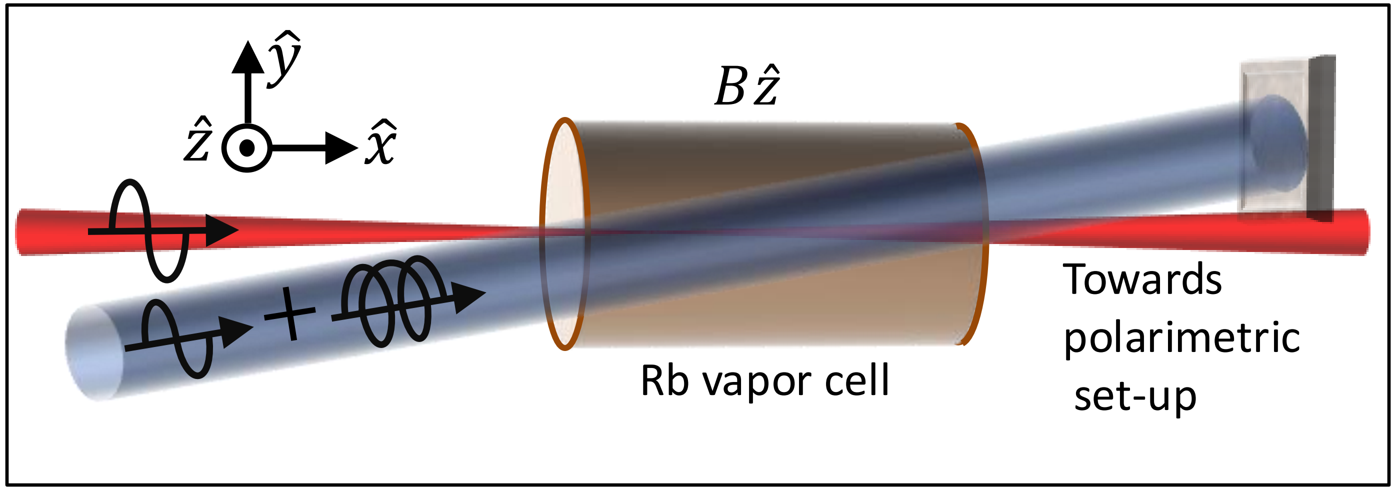
$$x = \frac{(g_J - g_I)\mu_B B_\perp}{h\Delta_{hf}}$$

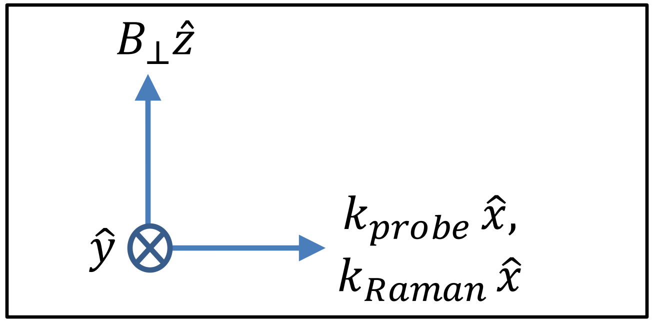




Opt. Express 26, 32168 (2018).

coherently driven atomic systems

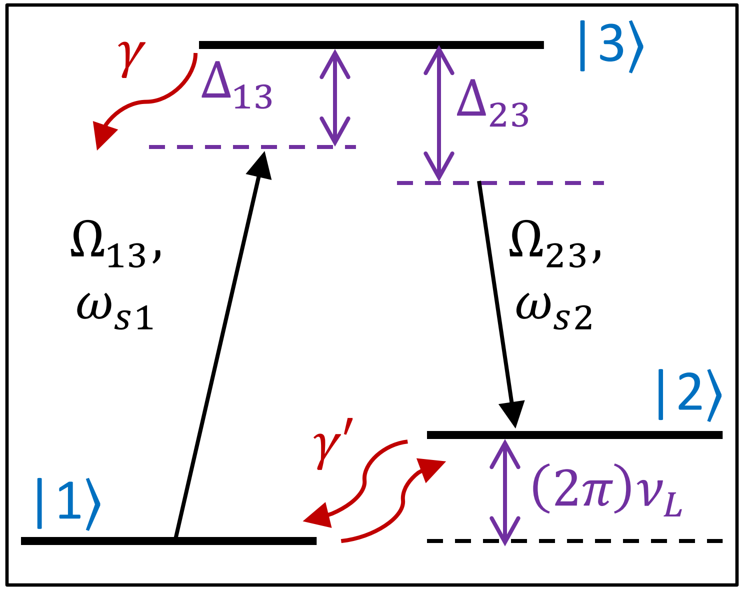


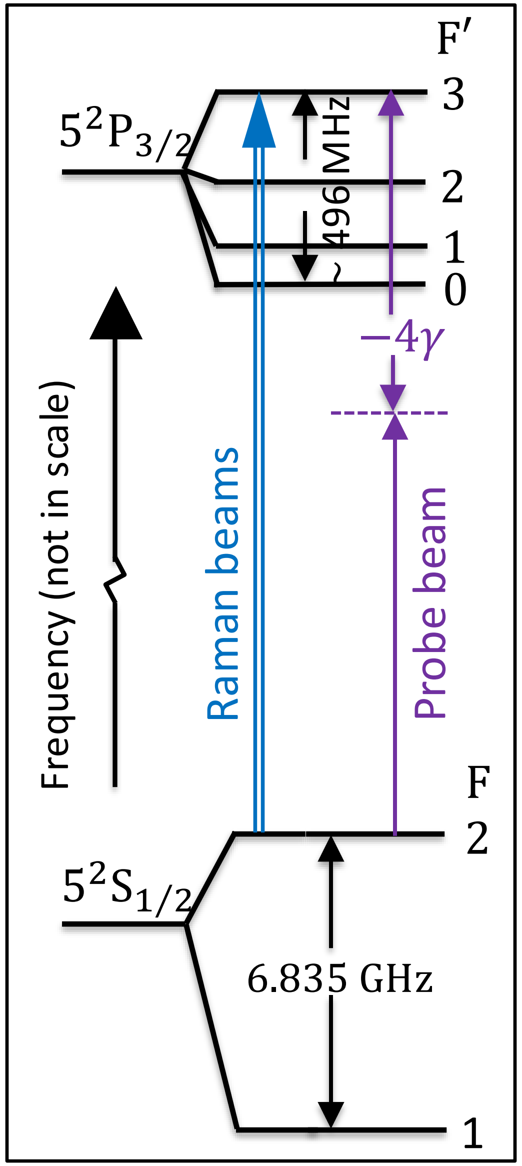


$|1\rangle \equiv |F = 2, m_F = -1\rangle$

$|2\rangle \equiv |F = 2, m_F = 0\rangle$

$|3\rangle \equiv |F' = 3, m_{F'} = 0\rangle$





Phys. Rev. Res. (2021).

Million fold signal enhancement: Thanks to Prof. C. V. Raman!

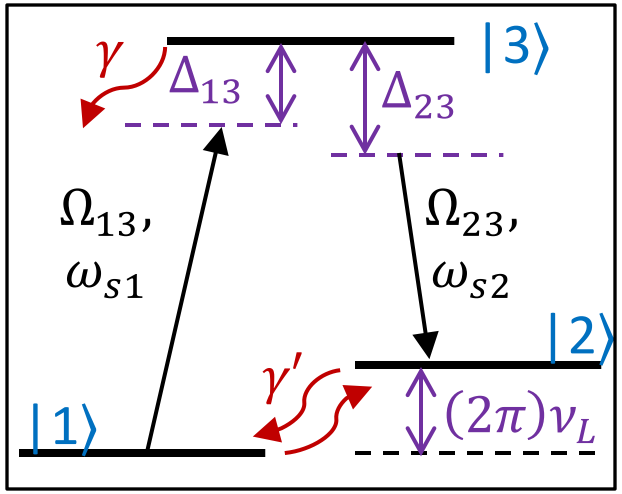
$$\frac{\mathcal{H}}{\hbar} = (\Delta_{23} - \Delta_{13})\mu^\dagger\mu - \Delta_{13}\sigma^\dagger\sigma - \Omega_{13}(\sigma + \sigma^\dagger) - \Omega_{23}(\mu + \mu^\dagger),$$

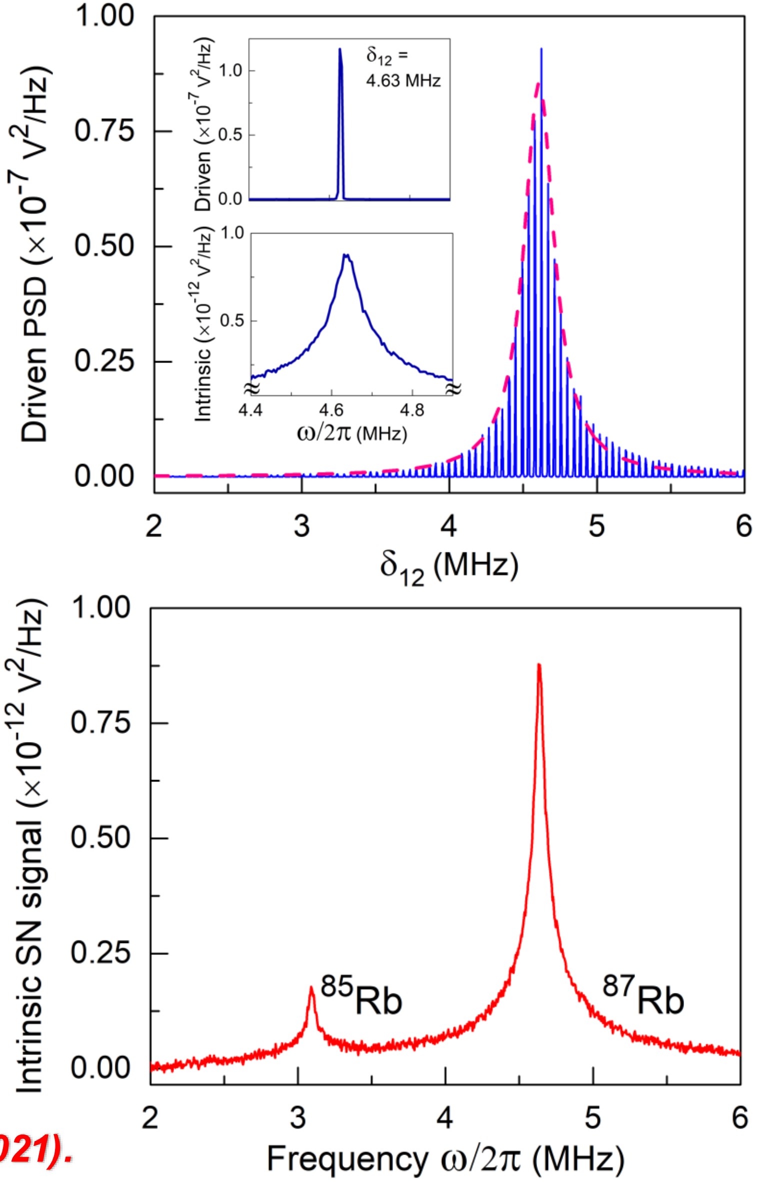
$$\sigma^\dagger = |1\rangle\langle 3|,\ \mu^\dagger = |2\rangle\langle 3|,\ \nu^\dagger = |1\rangle\langle 2|$$

$$P(\omega) = \delta(\omega + \omega_{s2} - \omega_{s1})|\rho_{21}|^2$$

$$\omega = \omega_{s1} - \omega_{s2} =: 2\pi\delta_{12}$$

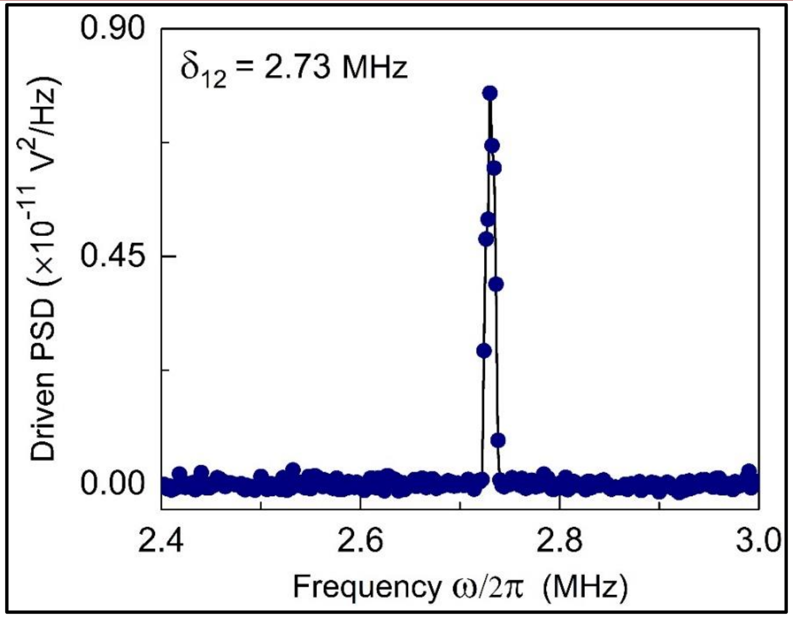
$$2\pi\delta_{12} = 2\pi\nu_L - (\Delta_{23} - \Delta_{13})$$

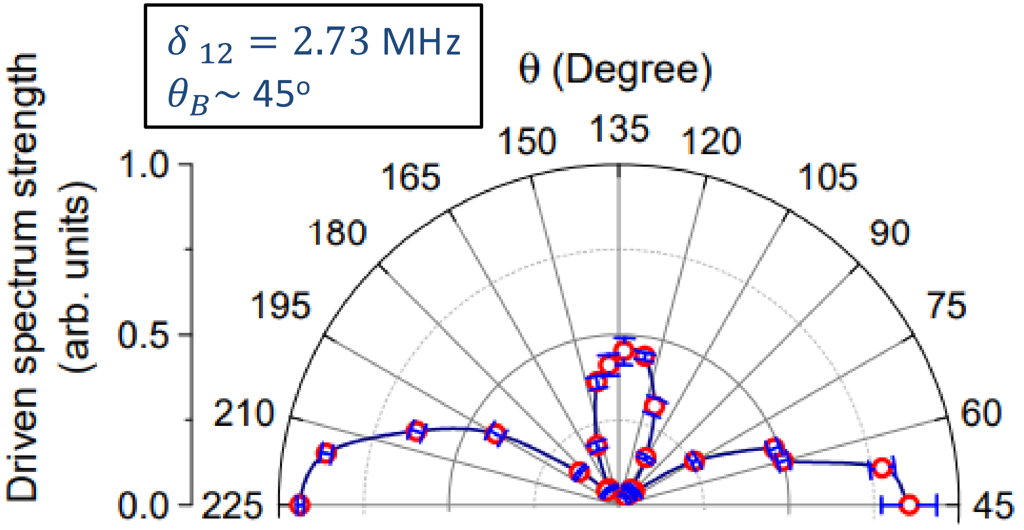


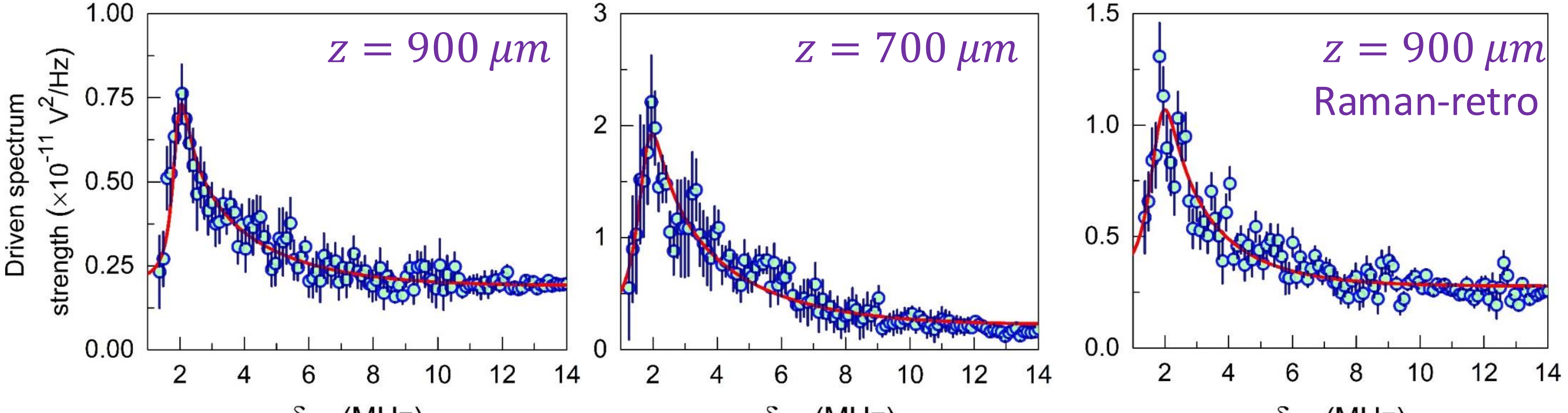


Phys. Rev. Res. (2021).

Driven spectrum in cold atoms







Phys. Rev. Res. (2021).

RDSNS Magnetometer operation

BREIT-RABI FORMULA FOR CALCULATION OF ENERGY OF ZEEMAN LEVELS

$$E_{F,m_F} = \frac{-\Delta_{\rm hf}}{2(2I+1)} - g_I \mu_N B m_F \pm \frac{\Delta_{\rm hf}}{2}\sqrt{1 + \frac{4m_F}{2I+1}x + x^2}$$

Where, $x = (g_J \mu_{\rm B} + g_I \mu_{\rm N})B/\Delta_{\rm hf}$,

$\Delta_{\rm hf}$ is energy separation between Hyperfine levels

g_I is nuclear g-factor

$\mu_N = \frac{e\hbar}{2m_p}$, is nuclear magneton

$\mu_B = \frac{e\hbar}{2m_e}$, is Bohr magneton

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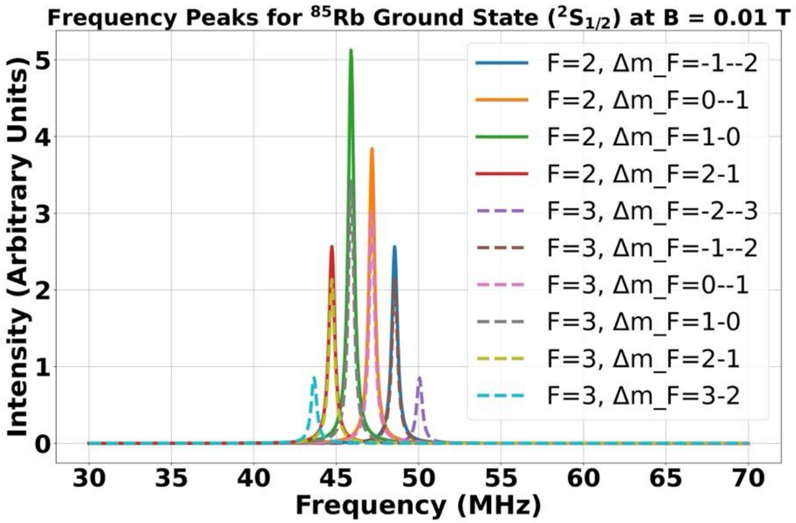
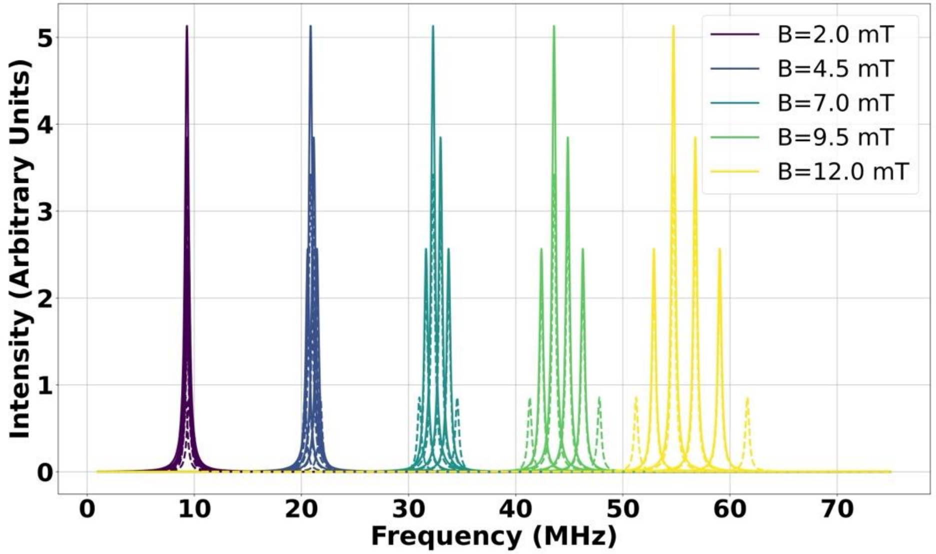
High Field





Quadratic Zeeman Effect: Breit Rabi fomula

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