Frequency Mesurementes of ^{3}He 2^{3}P Hyperfine Structure

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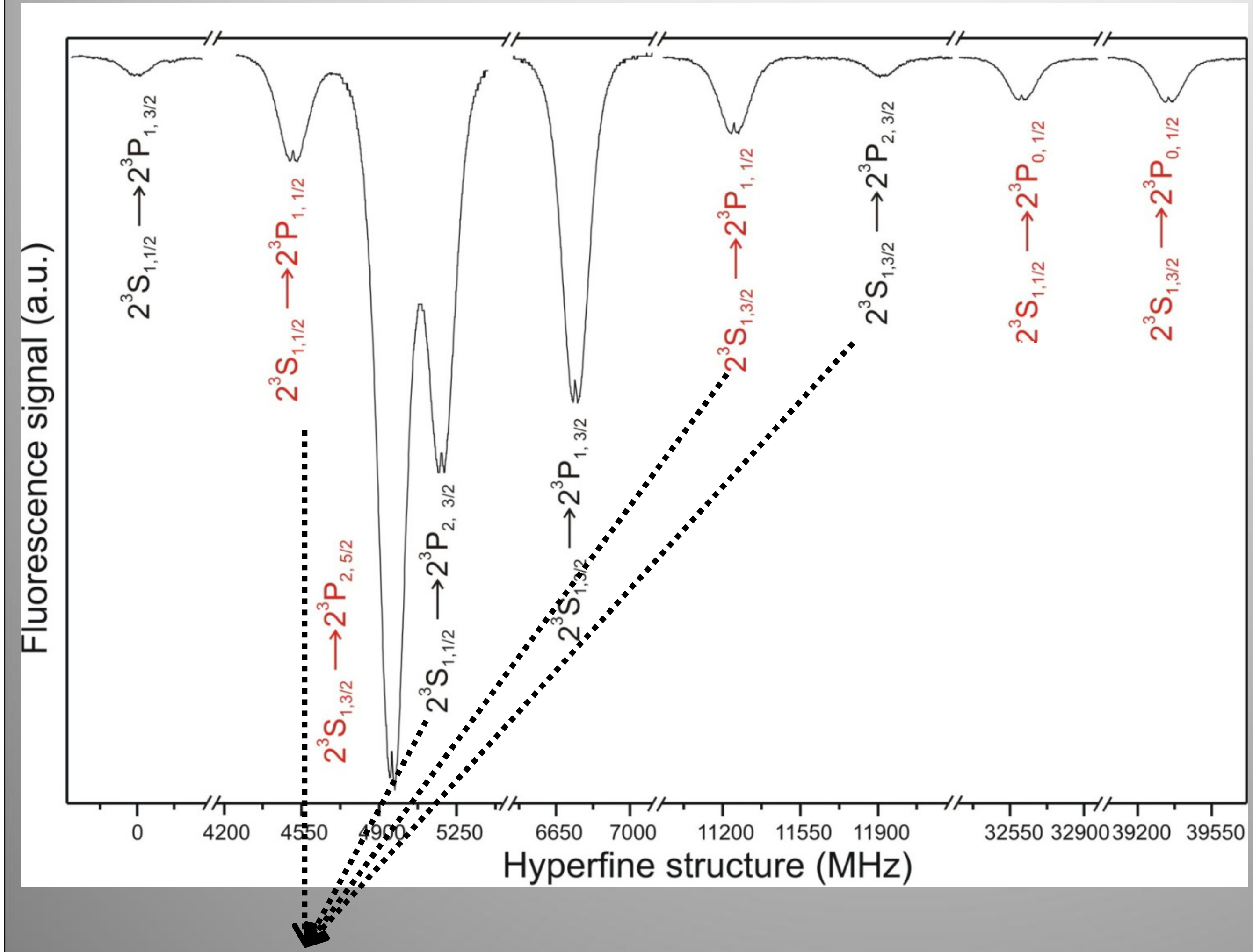
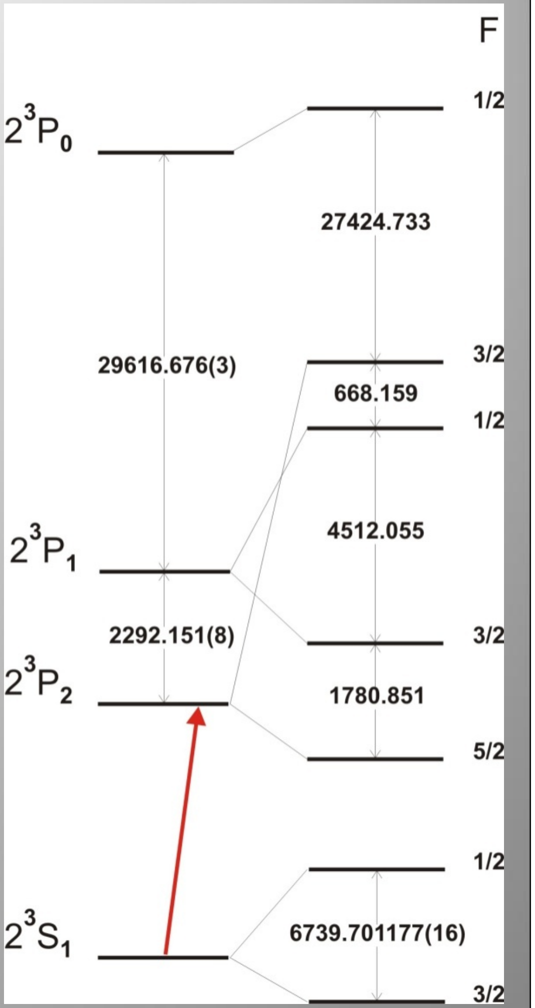
^{3}He structure at 1083nm

^{3}He Nuclear Spin $I = ½$ ➡ Hyperfine structure





$E_{1,1/2} < E_{2,3/2}$

Hyperfine structure in ³He: present situation

$$H_{hfs} = -2\mu_0 \sum_{i=1}^{2} \left\{ \frac{8\pi}{3} (\vec{s}_i \cdot \vec{\mu}) \delta(\vec{r}_i) - \frac{\vec{l}_i \cdot \vec{\mu}}{r_i^3} + \frac{1}{r_i^3} \left[\vec{s}_i \cdot \vec{\mu} - \frac{3(\vec{s}_i \cdot \vec{r}_i)(\vec{\mu} \cdot \vec{r}_i)}{r_i^2} \right] \right\}$$

$$H_{fen} = C\vec{I} \cdot \vec{S} + C'\vec{I} \cdot \vec{K} + D\vec{I} \cdot \vec{L} + 2\sqrt{10} E\vec{I} \cdot \left\{ \vec{S} C^{(2)} \right\}^{(1)}$$

Fenomenological hamiltonian

(E. Hinds *et al.*, *PRA*, **32** **(5)**, 2615 (1985)

Hyperfine coupling constants (HCC)

C, C' Fermi-contact interaction

D nuclear spin-orbit interaction

E nuclear spin-spin interaction

F (δ_{MP}, μ/M, a_e, δ_{QED}

Strong interaction for fine satates with the same n (in particular with the same L,S and F and different J → Exact diagonalization of the HF interaction matrix in each manifold of the states with the same n

- **HFS 2^3P splittings measured at 20 kHz accuracy** (J.D. Prestageet al. *PRL* **50**, 828 (1983))
- **HFS 2^3P splittings theoreticaly determined at 60 kHz accuracy** (Morton *et al.* Can. J. Phys, **82**, 835 (2005

Motivations

- nuclear structure in ^{3}He

Hyperfine interaction constants $\Delta\nu_{mes} \longrightarrow H_{HFS}$

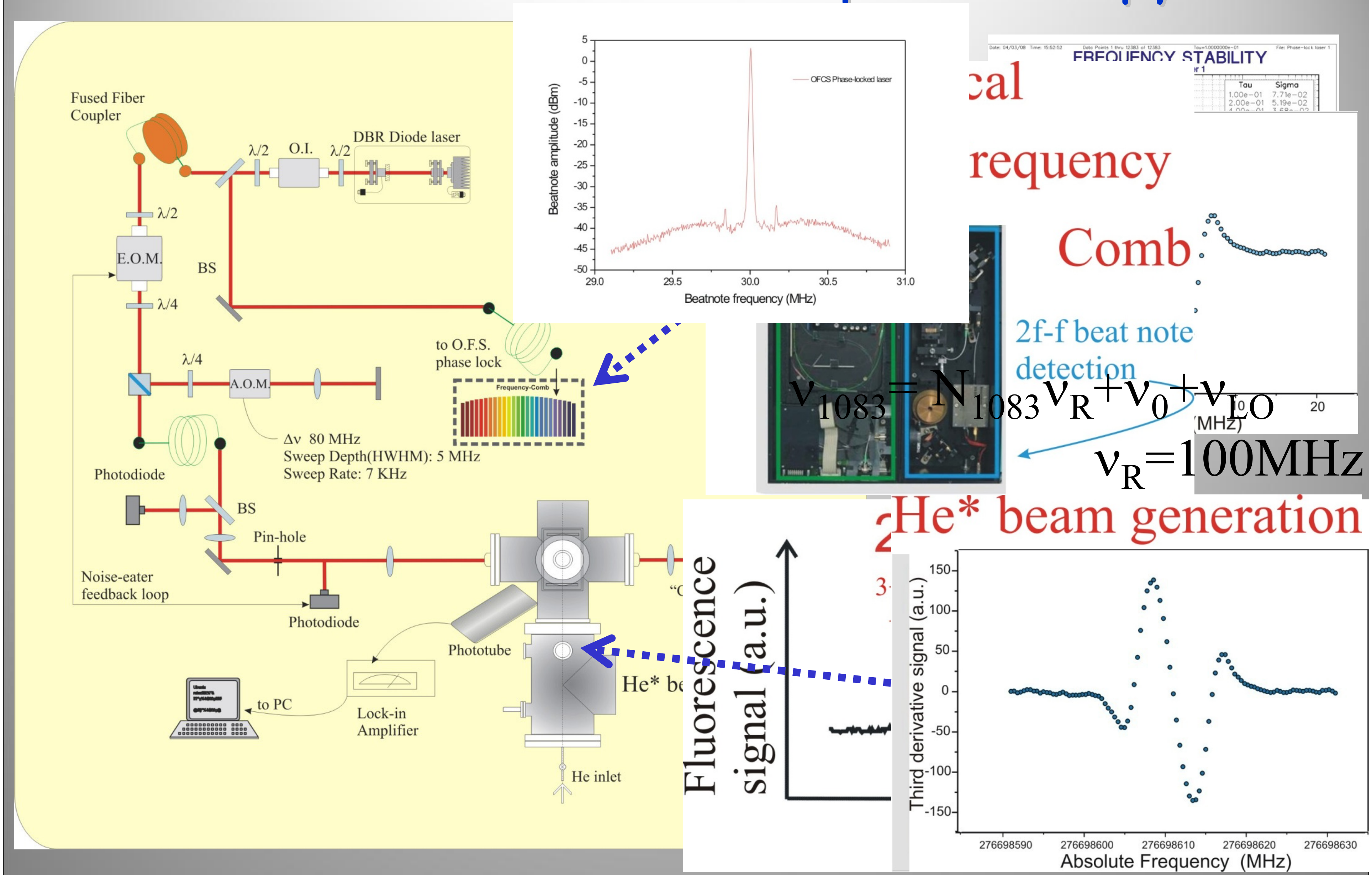
Hyperfine shifts $H_{HFS} \longrightarrow \delta\nu_{HFS}$

- ^{3}He nuclear charge radius

Isotope shift $\Delta\nu_{mes.} = \Delta\nu_{cal.}(M_{3,4}, R_{3,4})$

- test of He QED theory by measuring Lamb Shifts of Helium levels

OFCS-assisted Precision spectroscopy in He



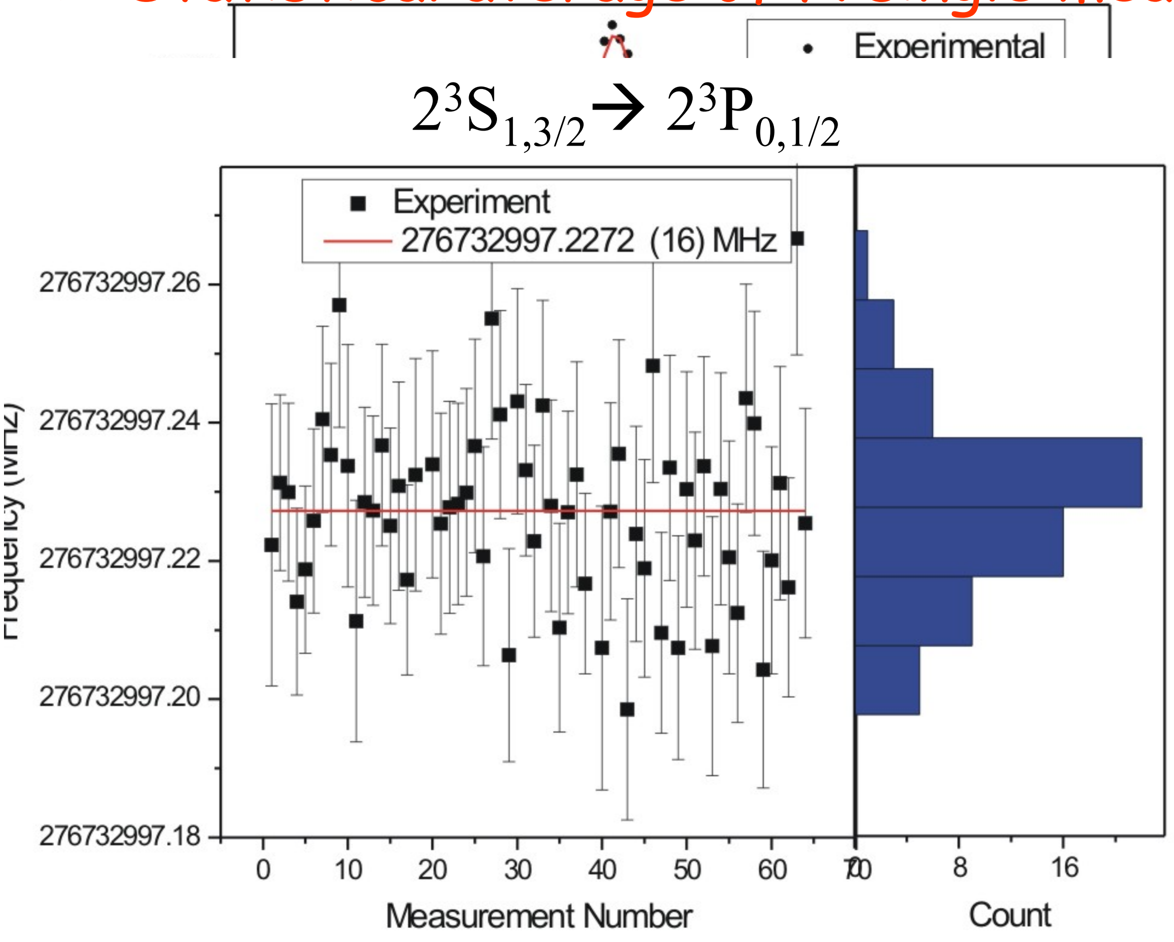
$\nu_{1083}=N_{1083}\nu_R+\nu_0+\nu_{LO}$

$\nu_R=100MHz$

- Absolute frequency against GPS-Rb-Quartz locked OFCS
- Fluorescence saturation spectroscopy in a metastable He beam

Measurement procedure

- ➢ Line center measurement for each recorded spectrum
- ➢ Statistical average of N single measurements



$2^3S_{1,3/2} \rightarrow 2^3P_{0,1/2}$

ities

Line center uncertainty ~5-20 kHz (S/N limited)

Statistical uncertainty ~1 kHz by averaging few tens of measurements

083nm

ansitions

differences

50-50 kHz

200-1 kHz

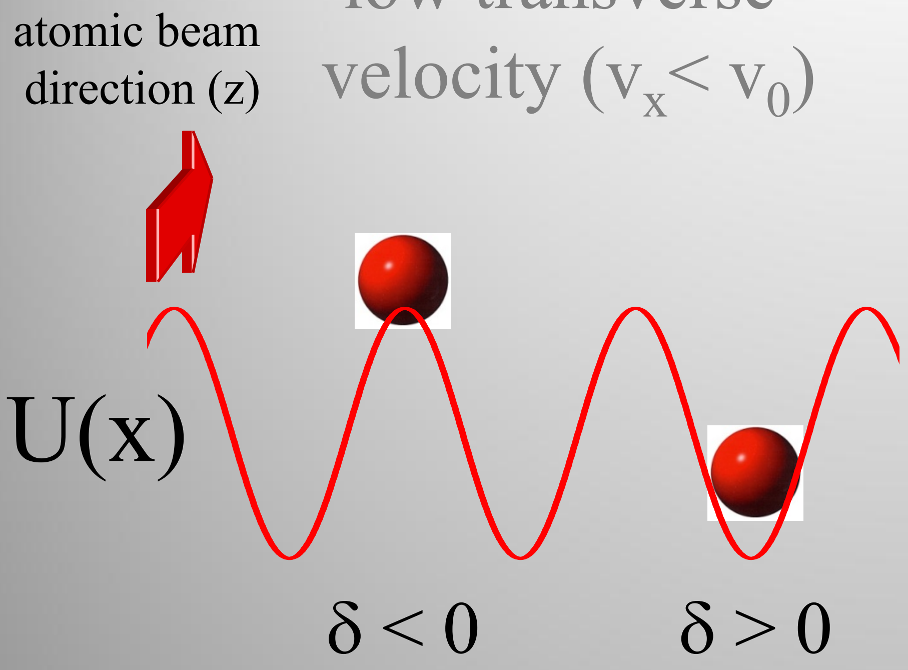
(1.4) kHz	(1.4) kHz
- 0.1) kHz	(< 1- 0.1) kHz
0.3) kHz	(0.3) kHz

Systematical effects: light-induced-mechanical shift

low transverse velocity ($v_x < v_0$)

high transverse velocity ($v_x > v_0$)

$F_x \propto \delta\, v_x$



$\delta > 0$ Doppler heating

$\delta < 0$ Doppler cooling

in both cases:

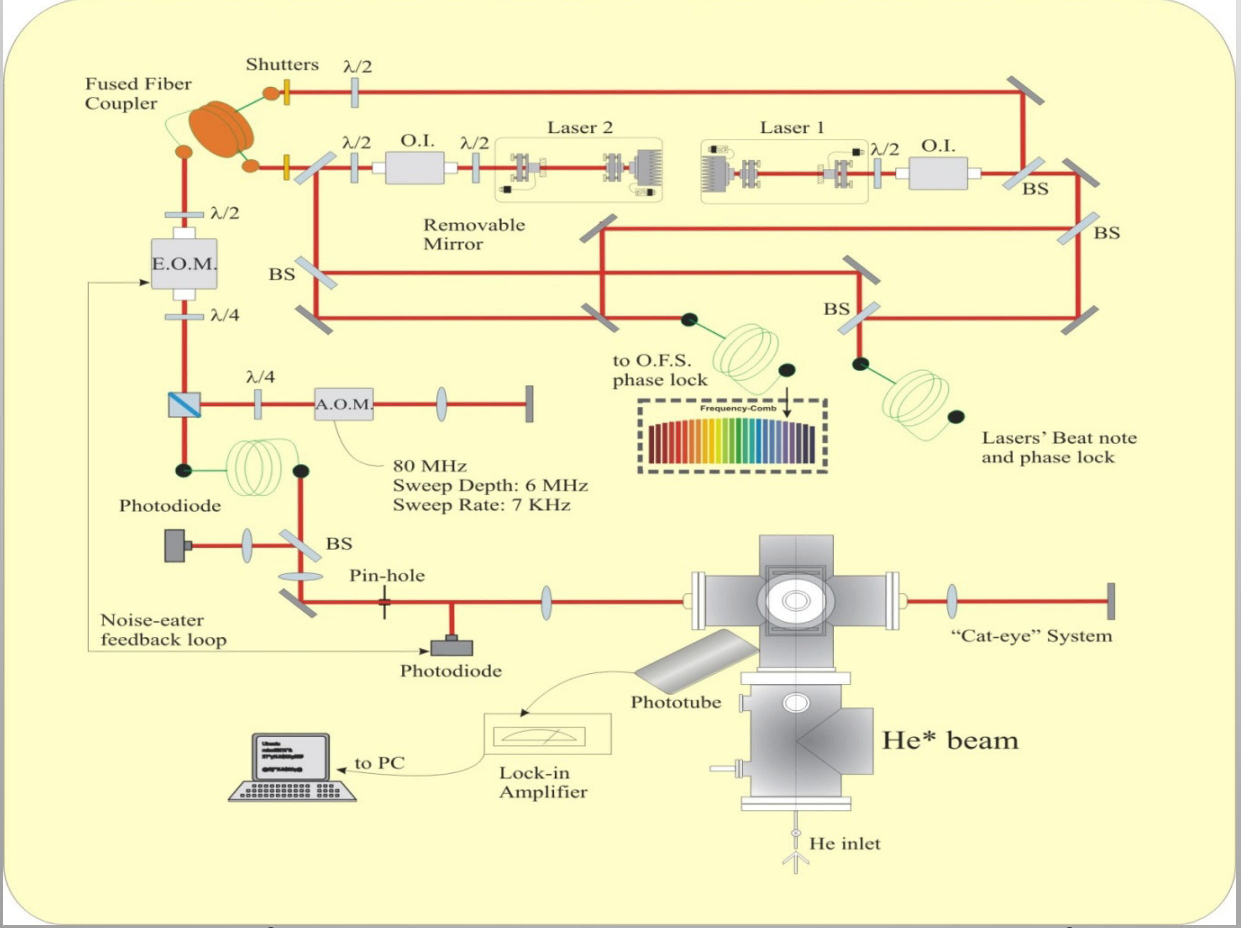
blue shift of observed line-center

F. Minardi, *et al.*, PRA **60**, 4164 (1999)

It depends strongly of the effective interaction time which is less for the open optical -pump transitions

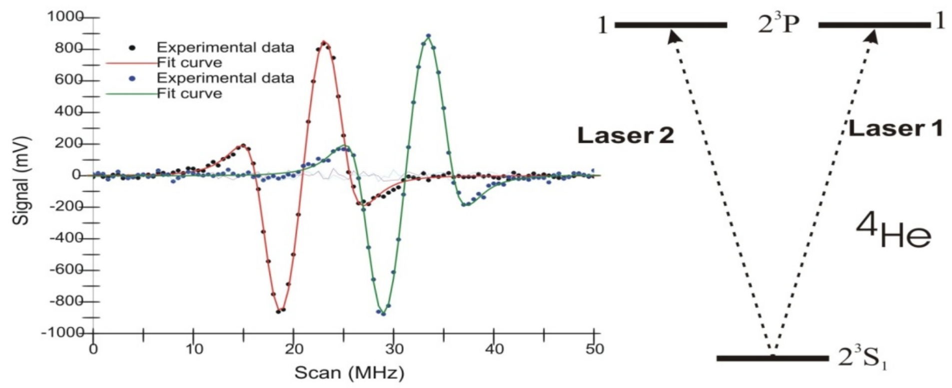
OFCS-assisted multi-resonant He spectroscopy

New present experiment



- Simultaneous frequency measurements of optical transitions and microwave splittings (HFS, FS and IS)
- V and Λ coherences and Ramsey fringes spectroscopy

Characterization of OFCS-assisted multi-resonant He spectroscopy

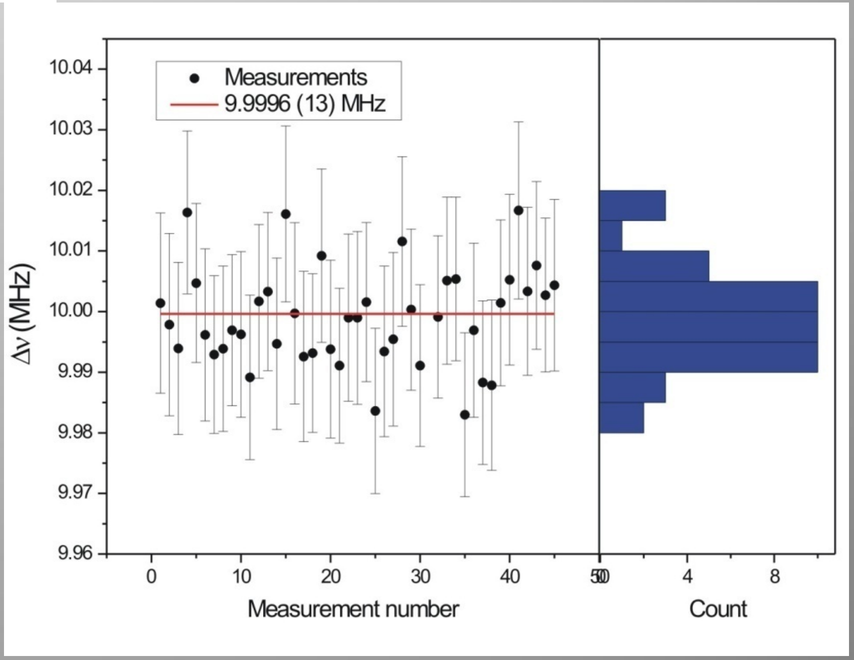


(The two lasers are 10 MHz apart for sake of clarity).

Both lasers resonant with the same transition

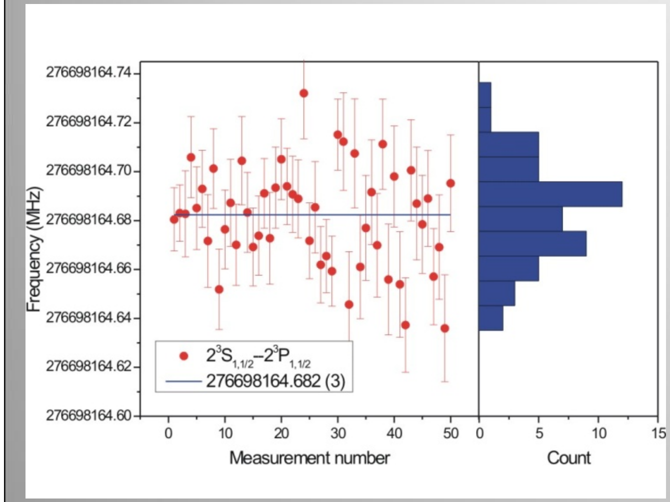
measurement of the frequency difference

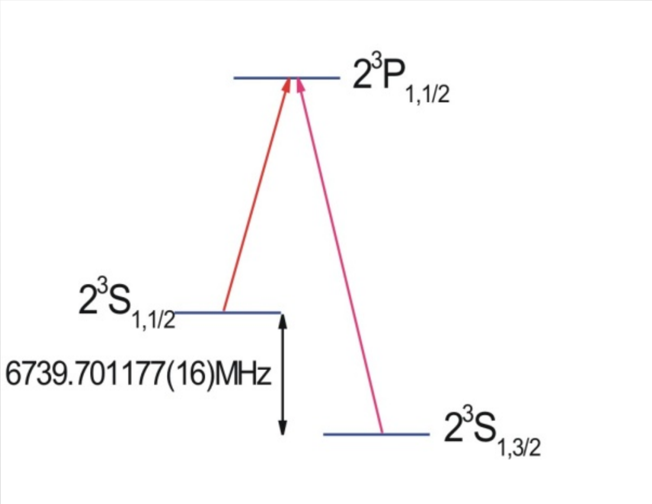
frequency difference is 10MHz at 1 kHz uncertainty

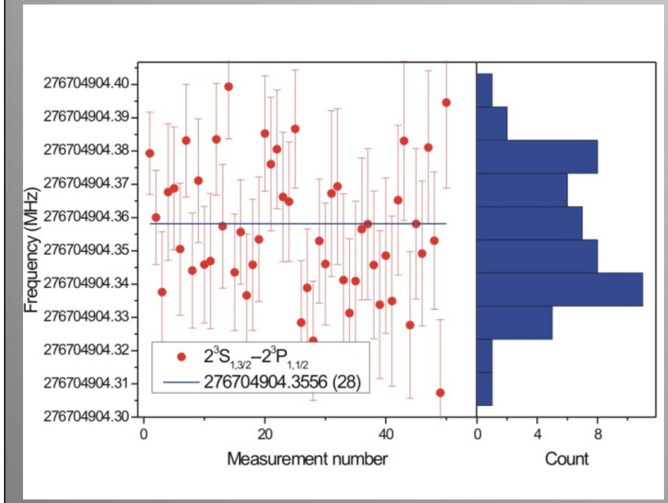


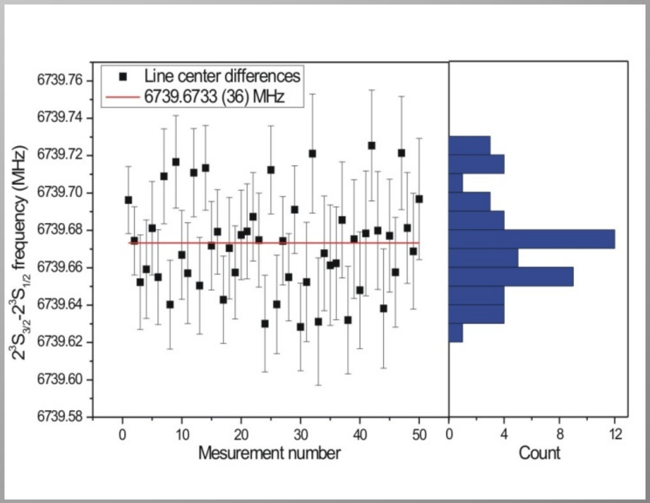
Measuring 2^3P HFS ….

The accuracy must be controlled by measuring transitions whose difference is the well known $2^3S_{1,3/2}$-$2^3S_{1,1/2}$ HFS (S.D. Rosner and F.M. Pipkin, *PRA* **1**, 157 (1970))









Measuring 2^3P HFS ….

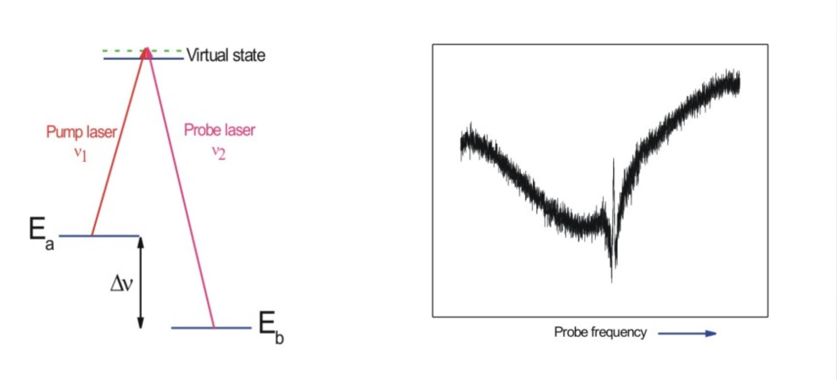
HFS splitting	$2^3S_{1,3/2}$ - $2^3S_{1,1/2}$ $\Delta\nu_S$ (kHz)		$2^3P_{1,1/2}$ -$2^3P_{0,1/2}$ $\Delta\nu_{P,01}$ (kHz)		$2^3P_{2,5/2}$ - $2^3P_{1,1/2}$ $\Delta\nu_{P,21}$ (kHz)		$2^3P_{2,5/2}$ - $2^3P_{0,1/2}$ $\Delta\nu_{P,20}$ (kHz)	
	$\nu_1 - \nu_2$	$\nu_4 - \nu_8$	$\nu_1 - \nu_4$	$\nu_2 - \nu_8$	$\nu_4 - \nu_7$	$\nu_7 - \nu_8$ $+\Delta\nu_S$	$\nu_1 - \nu_7$	$\nu_2 - \nu_7$ $+\Delta\nu_S$
Mean value	6739692,5 (3,9)	6739673,6 (4,1)	28092871,6 (3,2)	28092852,7 (4,7)	6292871,8 (3,8)	6292899,4 (4,0)	34385743,4 (3,0)	34385752,0 (4,4)
MS + LS + 2nd DS	7 (1,4)	30 (1,4)	20 (1,4)	43 (1,4)	140 (1,4)	133 (1,4)	120 (1,4)	90 (1,4)
Final frequency	**6739699,5 (4,8)**	**6739703,6 (4,8)**	**28092891,6 (4,1)**	**28092895,7 (5,4)**	**6293011,8 (4,6)**	**6293032,,4 (4,7)**	**34385863,4 (4,0)**	**34385842,0 (5,2)**
Previous Exp.	6739701,17 7 (16)	6739701,17 7 (16)	28092892 (20)	28092892 (20)	6292906 (20)	6292906 (20)	34385798 (20)	34385798 (20)
Difference	**1,7 (4,8)**	**-2,4 (4,8)**	**0,4 (20,4)**	**-3,7 (20,7)**	**-105,8 (20,5)**	**-126,4 (20,5)**	**-65,4 (20,4)**	**-44,0 (20,6)**
Theory	67370 (60)	673970 (60)	28092869 (60)	28092869 (60)	6293071 (60)	6293071 (60)	34385940 (60)	34385940 (60)
Difference	**0,5 (85,0)**	**-3,6 (85,0)**	**-22,6 (85.0)**	**-26,7 (85,0)**	**60,8 (85,0)**	**39,4(85,0)**	**77,4 (85,0)**	**98.0 (85,0)**

Previous Experiments: J.D. Prestageet al. *PRL* **50**, 828 (1983)

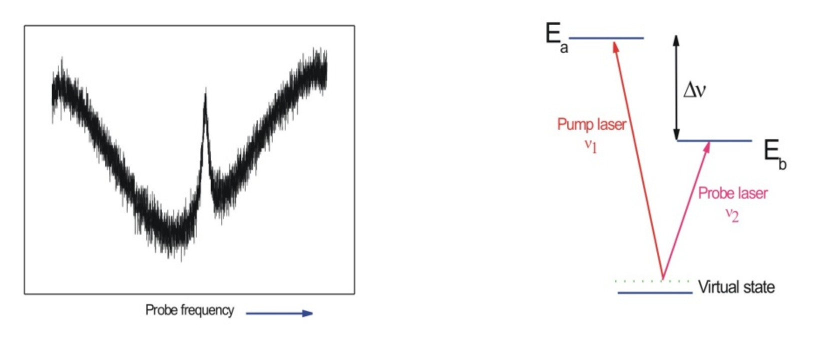
Theory: Morton *et al.* Can. J. Phys, **82**, 835 (2005)

Coherent Electromagnetic Induced Transparency (EIT)

The population of E_a and E_b states is coherently coupled by the phase-coherent co-propagate laser fields



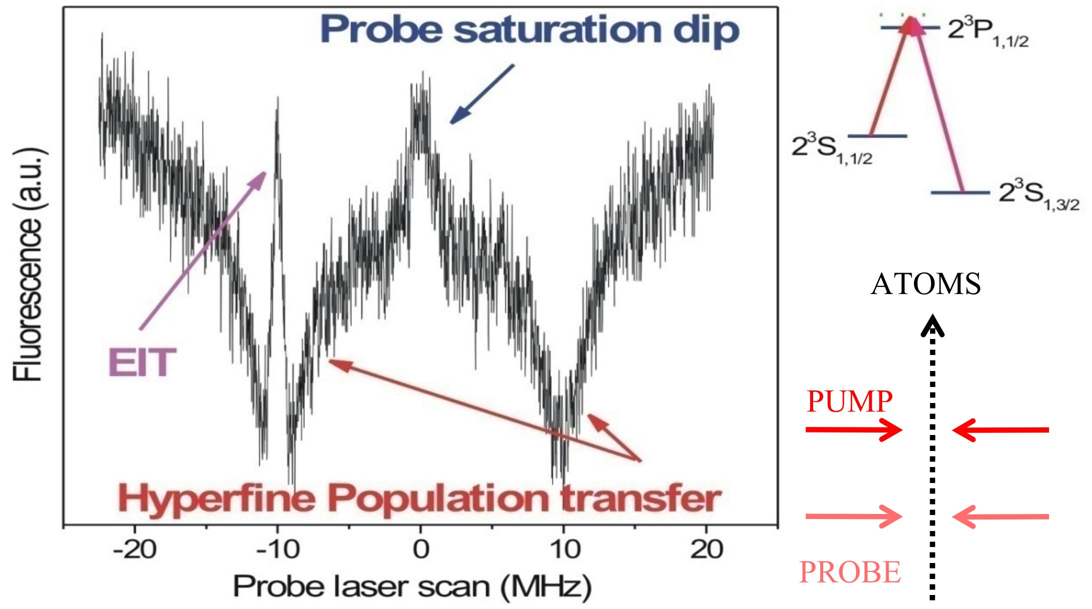
Λ Scheme → Dark resonance



V Scheme → EIT

- Resonance frequency $\Delta\nu=\nu_2-\nu_1$ → To measure splittings
- Homogeneous effect → All transversal velocity classes contribute to the signal
- Co-propagating lasers → No meccanical-light shifts
- Doppler effect scales with $\Delta\nu$ → Smaller 2nd Doppler shift

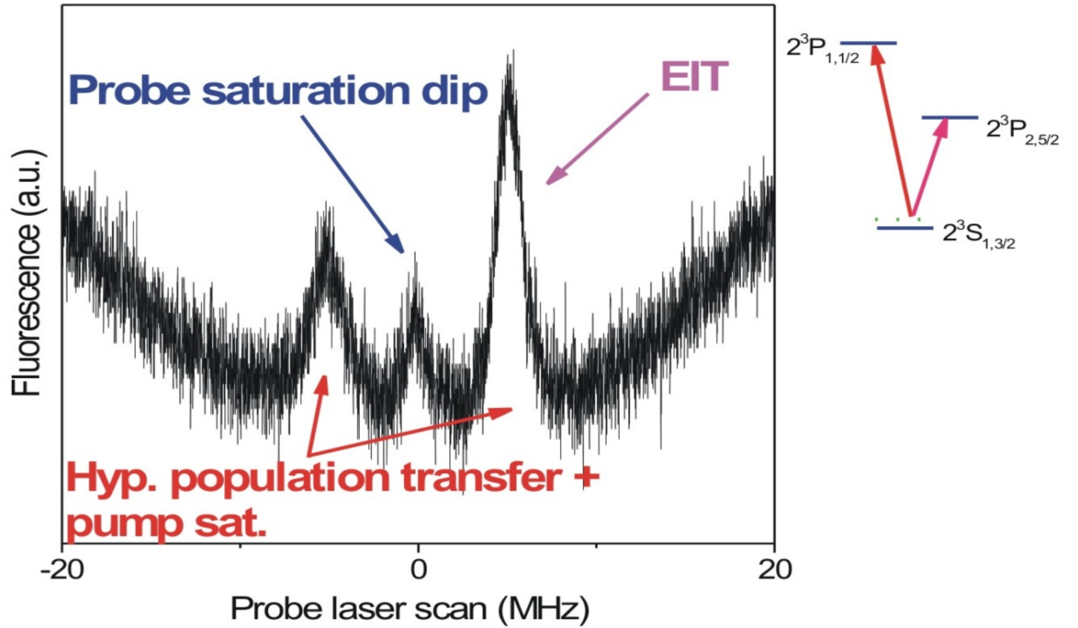
OFCS-assisted EIT He spectroscopy



Both lasers together interact with the atoms in forward-backward configuration

↓

To minimize 1st order Doppler and residual recoil

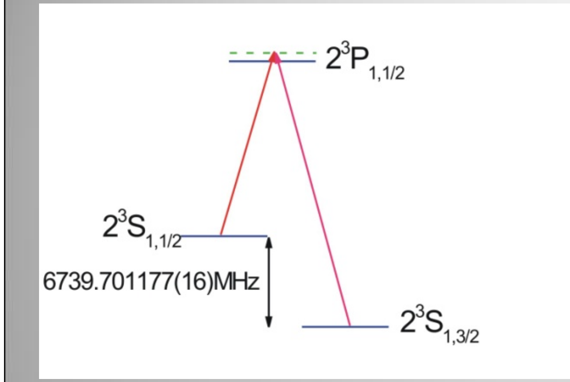


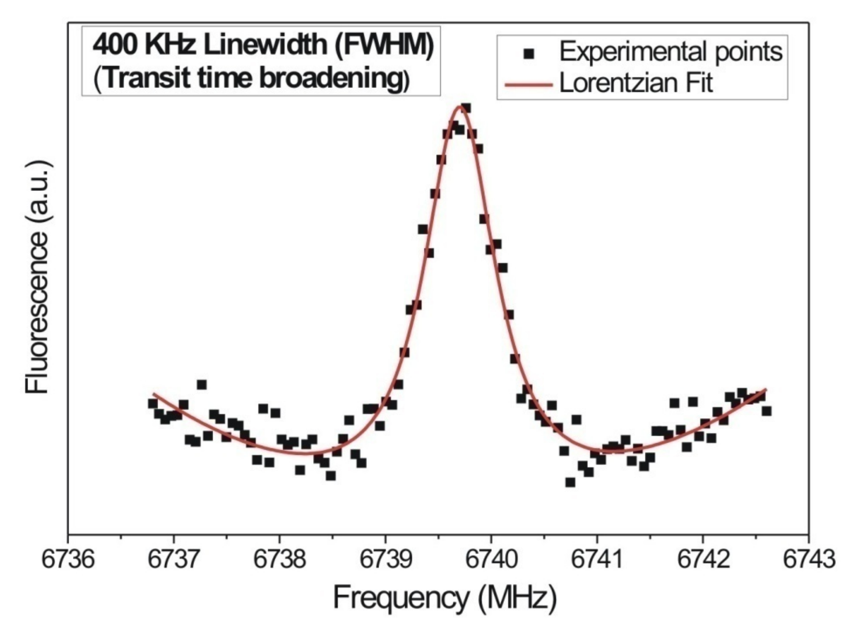
Pump laser accurately detuned from the line center

↓

To avoid frequency shift from the saturation dip

Measuring 2^3S HFS with EIT ^3He spectroscopy

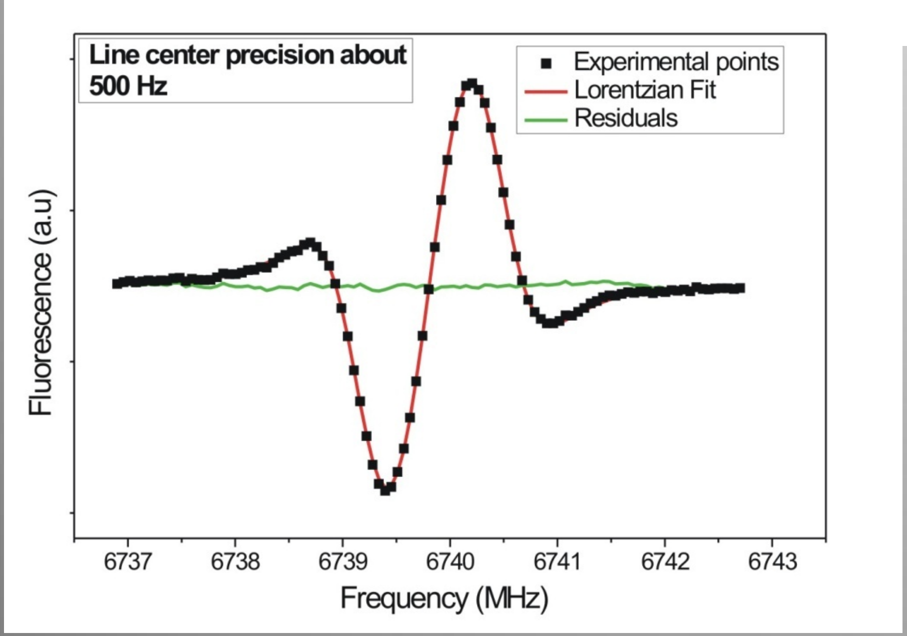




Narrow linewidth and high S/N

↓

better precision

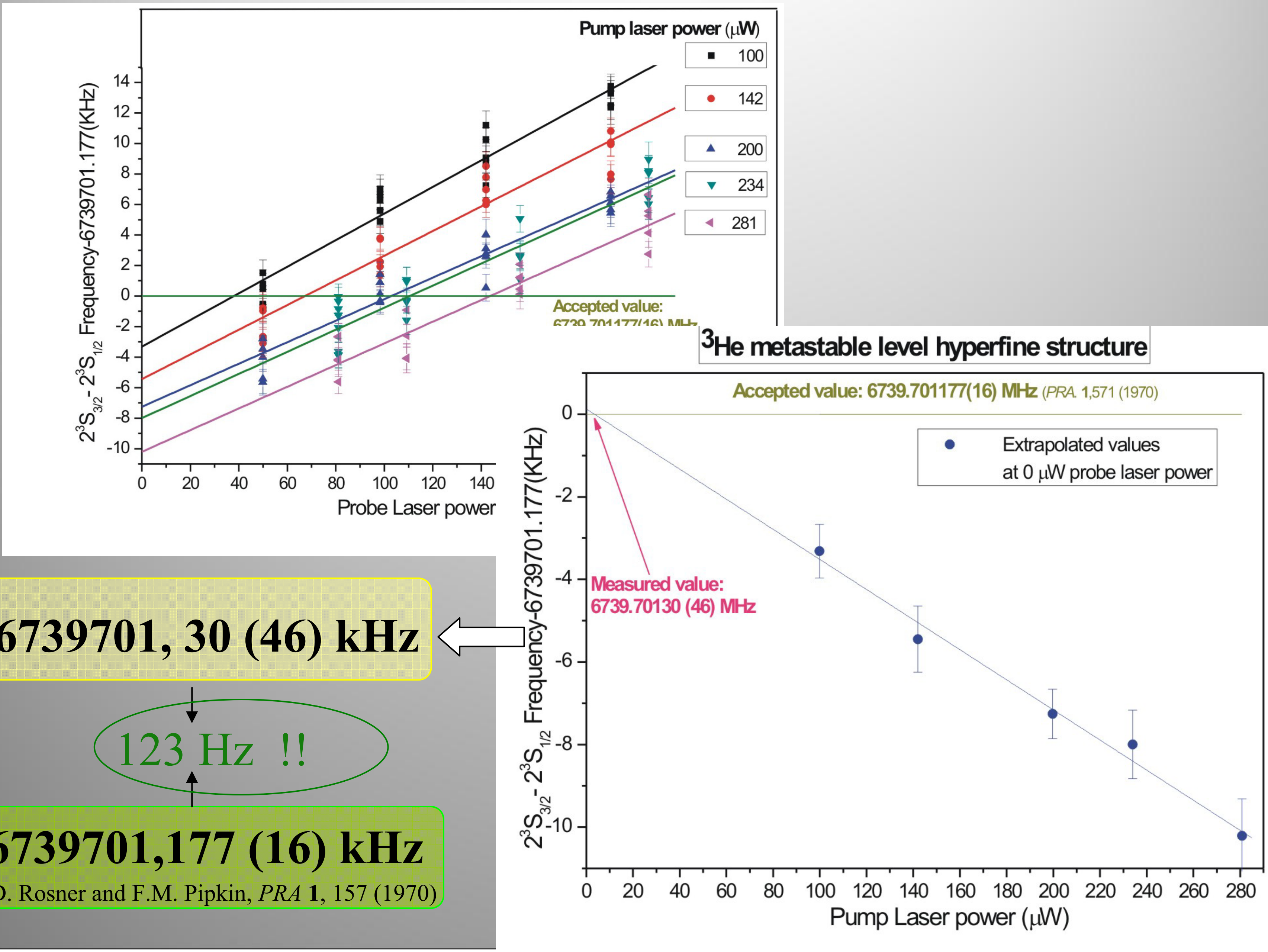


- Sub-kHz accuracy by averaging few measurements
- AC-Stark shift must be considered

↓

Behavior vs pump and probe power

Measuring 2^3S HFS with EIT ^3He spectroscopy



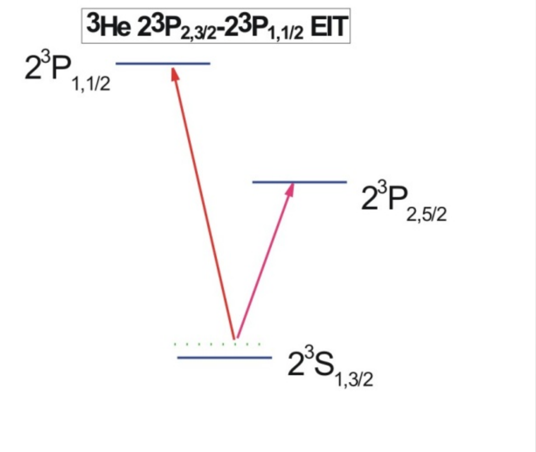
6739701, 30 (46) kHz

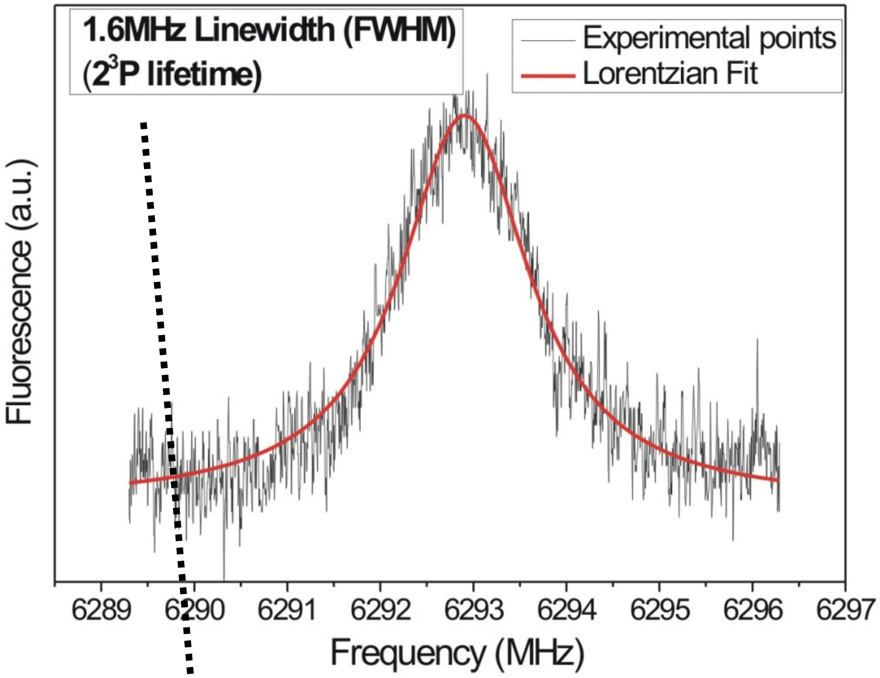
123 Hz !!

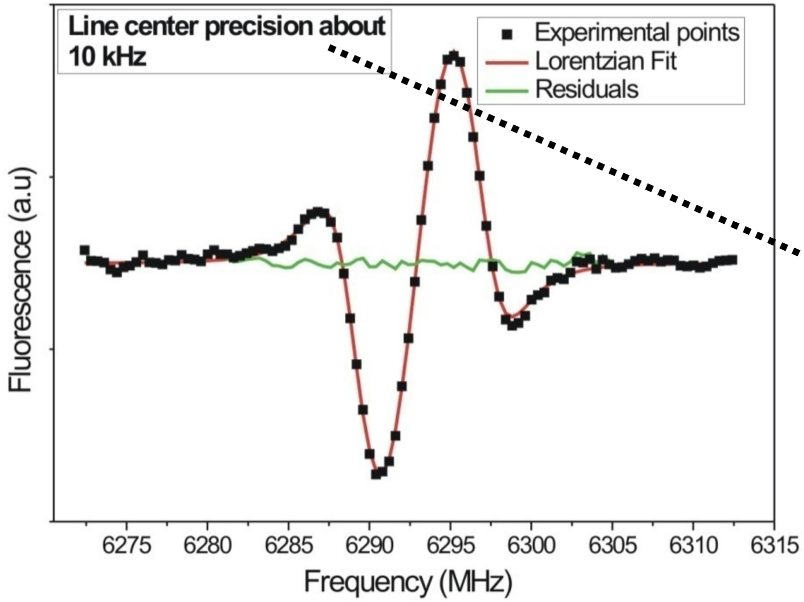
6739701,177 (16) kHz

S.D. Rosner and F.M. Pipkin, *PRA* **1**, 157 (1970)

Measuring 2^{3}P HFS with EIT ^{3}He spectroscopy

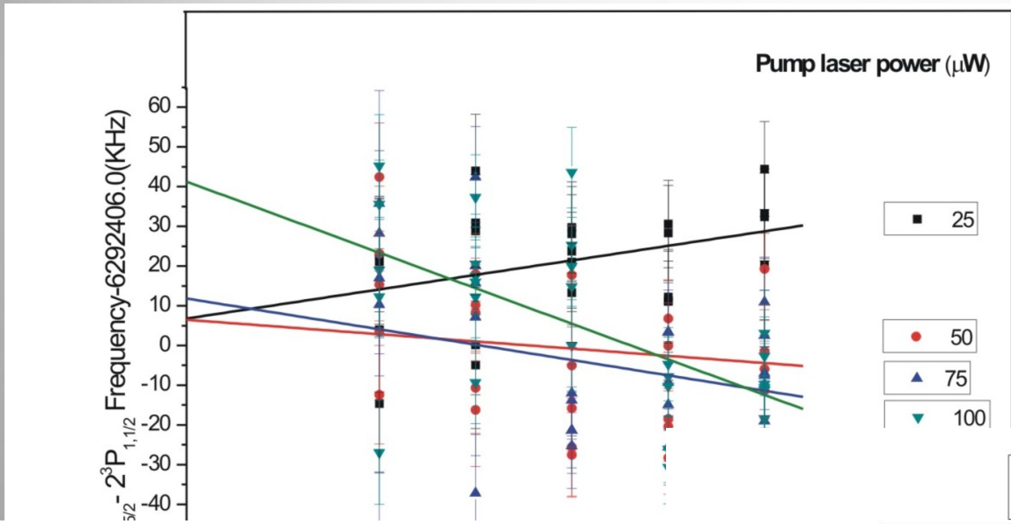




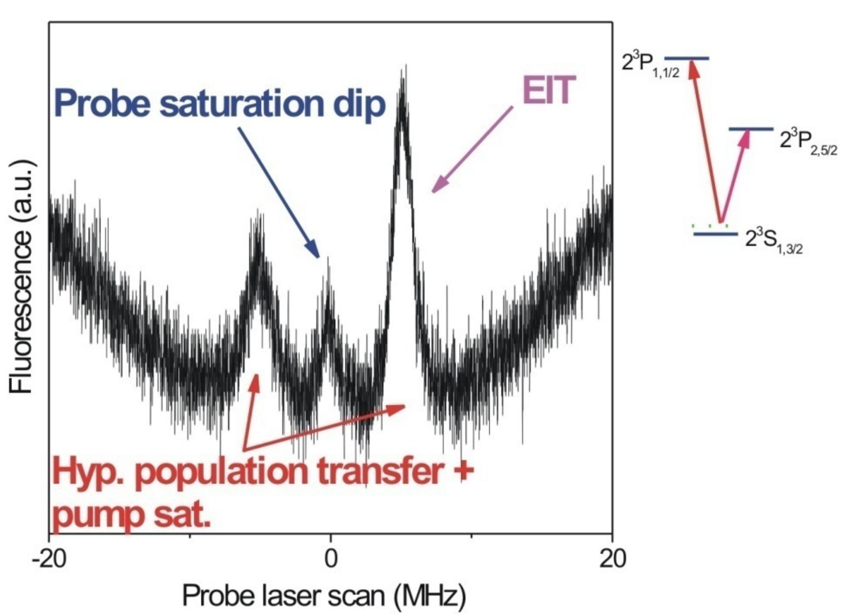


Similar precision than saturation spectroscopy measurements

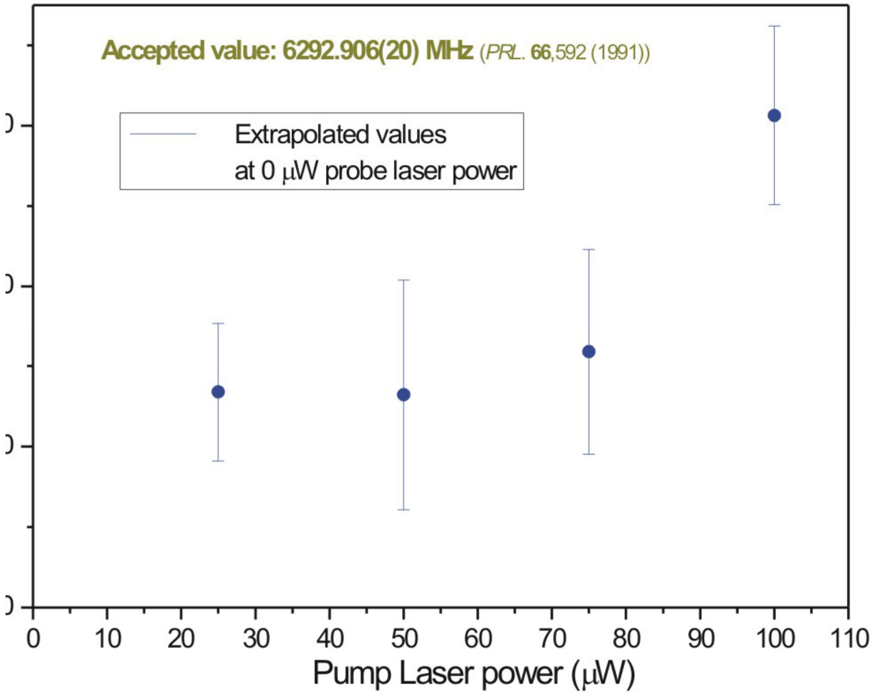
Measuring 2^3P HFS with EIT ^3He spectroscopy



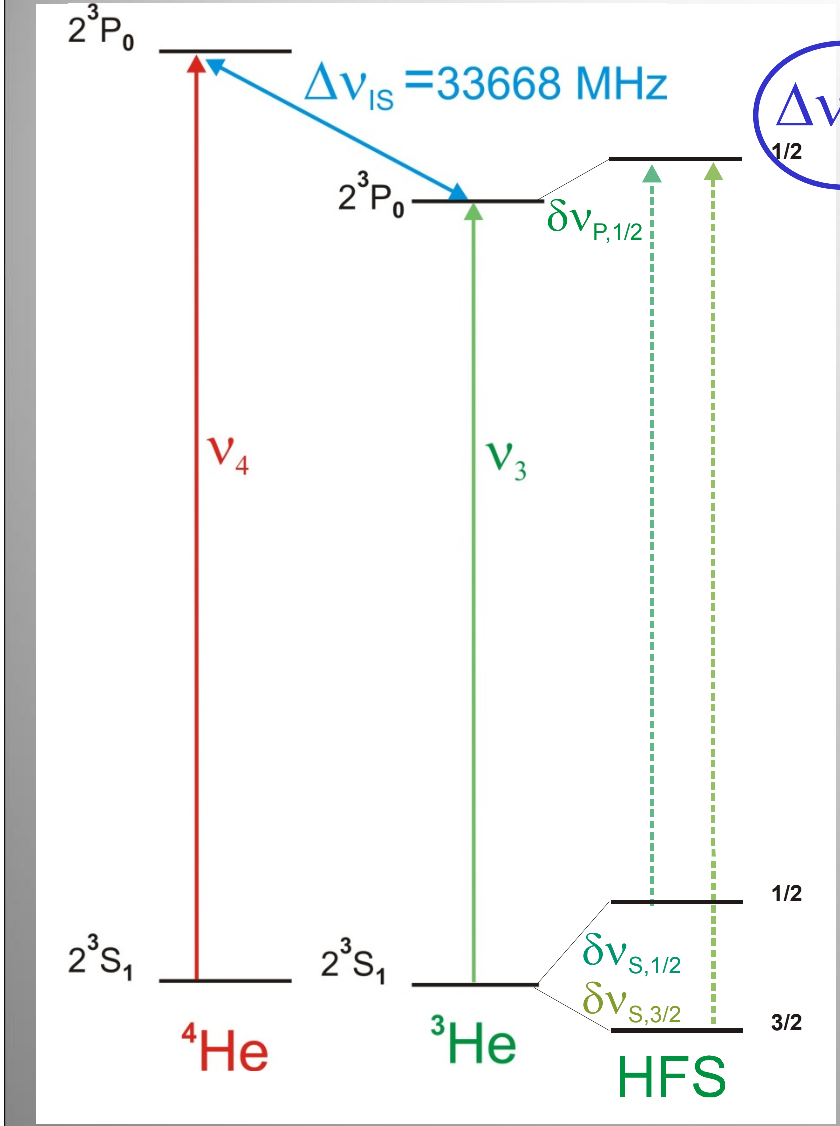
Some residual Mechanical shift is present from population transfer background



^3He $2^3P_{2,5/2}$-$2^3P_{1,1/2}$ hyperfine structure



Hyperfine shift determination in ^{3}He 2^3P



$$\Delta\nu_{IS} = \nu_4 - \nu_3 = \nu_4 - \nu_{3/2-1/2} - \delta\nu_{S,3/2} + \delta\nu_{P,1/2}$$

Theory

Measured

Determination of $\delta\nu_{P,1/2}$

Measuring 2^3P HF Shifts ….

Preliminary results for optical transitions

Transition	**$2^3S_{1,3/2}\rightarrow 2^3P_{0,1/2}$ ν_1 (kHz)**	**$2^3S_{1,1/2}\rightarrow 2^3P_{0,1/2}$ ν_2 (kHz)**	**$2^3S_{1,3/2}\rightarrow 2^3P_{1,1/2}$ ν_4 (kHz)**	**$2^3S_{1,3/2}\rightarrow 2^3P_{2,5/2}$ ν_7 (kHz)**	**$2^3S_{1,1/2}\rightarrow 2^3P_{1,1/2}$ ν_8 (kHz)**
Mean value	276732997227,2 (1,6)	276726257534,7 (3,6)	276704904355,6 (2,8)	276698611483.8 (2,6)	276698164682.0 (3)
MS + LS + 2nd DS	-60 (1)	-67 (1)	-80 (1)	-200 (1)	-110 (1)
1st DS	(1,4)	(1,4)	(1,4)	(1,4)	(1,4)
Residual Zeeman shift	(0,47)	(0,93)	(0,23)	(0,14)	(0,23)
OFS accuarcy	(0,3)	(0,3)	(0,3)	(0,3)	(0,3)
Final frequency	**276732997167,2 (2,4)**	**276726257467,7 (4,1)**	**276704904275,6 (3,3)**	**276698611283,8 (3,1)**	**276698164572,0 (3,5)**

Preliminary results for $2^3P_{0,1/2}$ and $2^3P_{1,1/2}$ HF shifts

Present work →

Our measurement →

^{3}He Transition (MHz)	$2^3S_{1,3/2} \rightarrow 2^3P_{0,1/2}$ 276732997.1672 (24)	$2^3S_{1,3/2} \rightarrow 2^3P_{1,1/2}$ 276704904.2756 (33)
^{3}He $2S_{1,3/2}$ HF shift (MHz)	-2246.5873	-2246.5873
^{4}He Transition (MHz)	$2^3S_1 \rightarrow 2^3P_0$ 276764094.7039 (24)	$2^3S_1 \rightarrow 2^3P_1$ 276734477.7525 (20)
^{3}He - ^{4}He IS (MHz)	33668.075 (1)	33667.8 (1)
^{3}He 2^3P HF shift (MHz)	**323.9510 (35)**	**1847.7358 (40)**
Prev. Measu. (MHz) Difference (kHz)	323.9503 (12) **-0.7 (3.6)**	
Theory (MHz) Difference (kHz)	323.954 (1) **3 (4)**	1847.761 (1) **25.2 (4.1)**

← Measured

← Theory

Previous Experiments: D. Shiner et al., *PRL*. **74**, 3553 (1995)

Theory: Morton *et al.* Can. J. Phys, **82**, 835 (2005)

Conclusions

- OFCS-assisted precision spectroscopy of ^{3}He 2^3S → 2^3P transitions and HF 2^3S and 2^3P splittings was simultaneously performed. Preliminary results are accuracy limited by statistics and Mechanical-shift corrections.
- HFS measurements by OFCS-assisted EIT spectroscopy were performed. The method is promising when residual pump-transfer population background will be cancelled. EIT spectroscopy with cold He can help to this issue.
- Preliminary values of $2^2P_{0,1/2}$, $2^3P_{1,1/2}$ HF shifts were determined by using frequency measurements of the optical transitions.

Helium team

INOA-CNR + LENS

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L. Consolino
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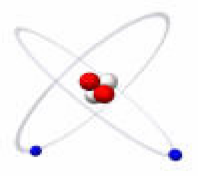
CIGMA project **(European Science Foundation and CNR)**

Precision spectroscopy with combs project **(Ente Cassa di Risparmio di Firenze)**

Why Precision spectroscopy of helium?

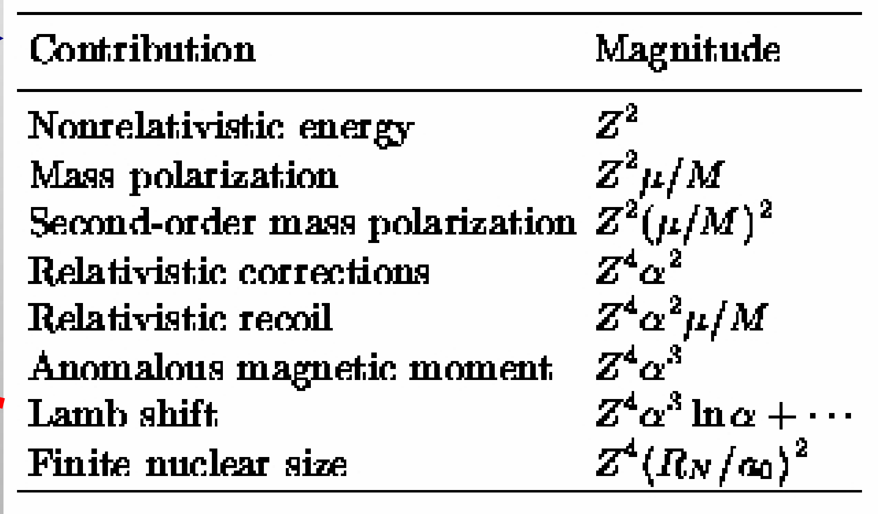


Simplest calculable three body atomic system

$$H_{\mathrm{at}} = H_{nr} + H_{\mathrm{rel}} + H_{\mathrm{QED}}$$

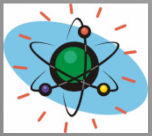
$$E = E_{nr} + \boxed{\Delta E_{rel,QED}}$$

Calculated E accuracies 10^{-8}-10^{-9} for the lower Rydberg levels



Contribution	Magnitude
Nonrelativistic energy	Z^2
Mass polarization	$Z^2\mu/M$
Second-order mass polarization	$Z^2(\mu/M)^2$
Relativistic corrections	$Z^4\alpha^2$
Relativistic recoil	$Z^4\alpha^2\mu/M$
Anomalous magnetic moment	$Z^4\alpha^3$
Lamb shift	$Z^4\alpha^3 \ln\alpha + \cdots$
Finite nuclear size	$Z^4(R_N/a_0)^2$

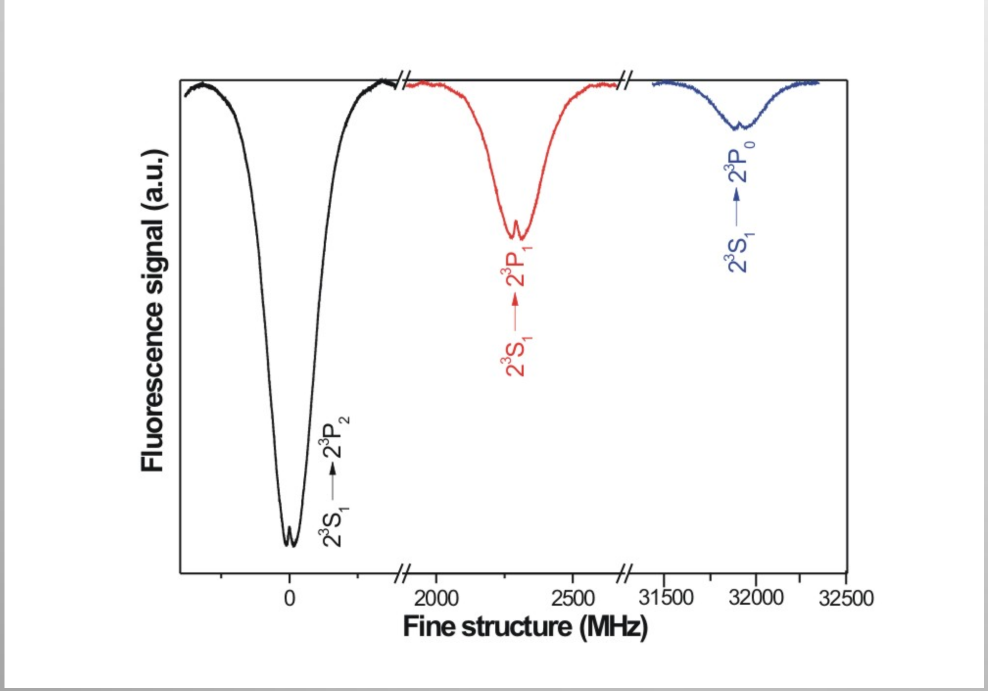
(Morton *et al.* Can. J. Phys, **82**, 835 (2005))

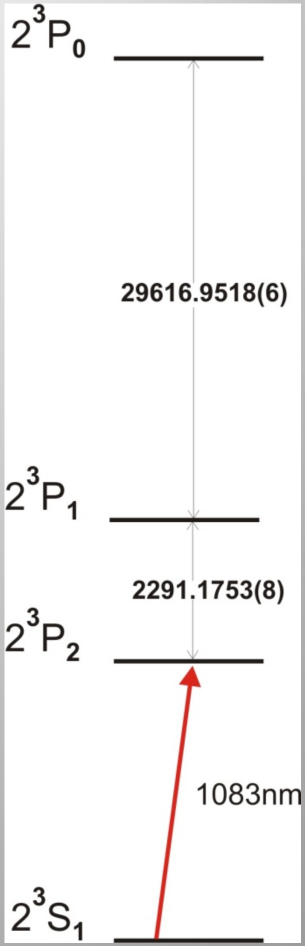


test of bounded two electron QED theory by measuring Lamb Shifts of Helium levels

He structure at 1083nm

^{4}He Nuclear Spin I = 0 ➡ Fine structure





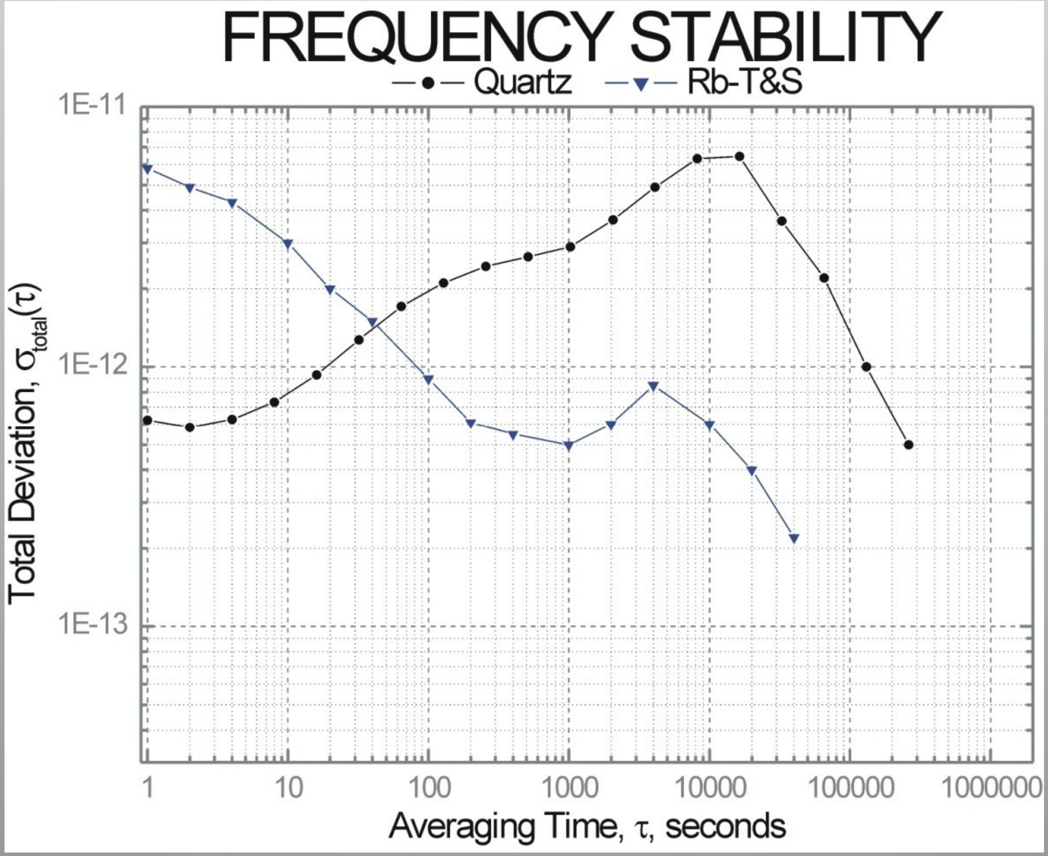
- **Absolute frequencies of optical transitions known at 10^{-12} accuracy** (P. Cancio et al. *PRL* **92**, 023001-1 (2004), *PRL* **97**,139903 (2006))
- **FS splittings known at 1kHz accuracy** (T. Zelevinsky et al. *PRL* **95**, 203001 (2005), G. Giusfredi et al. *Can. J. Phys*, **83**, 301 (2005), M.C. George et al. *PRL* **87**, 173002-1(2001), C. Storry et al. *PRL* **84**, 3274(2000))

Outline

- He structure at 1083 nm: motivations
- ^{3}He hyperfine fine structure (HFS): 2^3P level present situation
- OFCS-assisted precision spectroscopy in He
- HFS measurements by frequency difference of optical transitions
- HFS measurements by Electromagnetic Induced Transparency (EIT) spectroscopy
- $2^3P_{0,1/2}$, $2^3P_{1,1/2}$ hyperfine shift determinations
- Conclusions

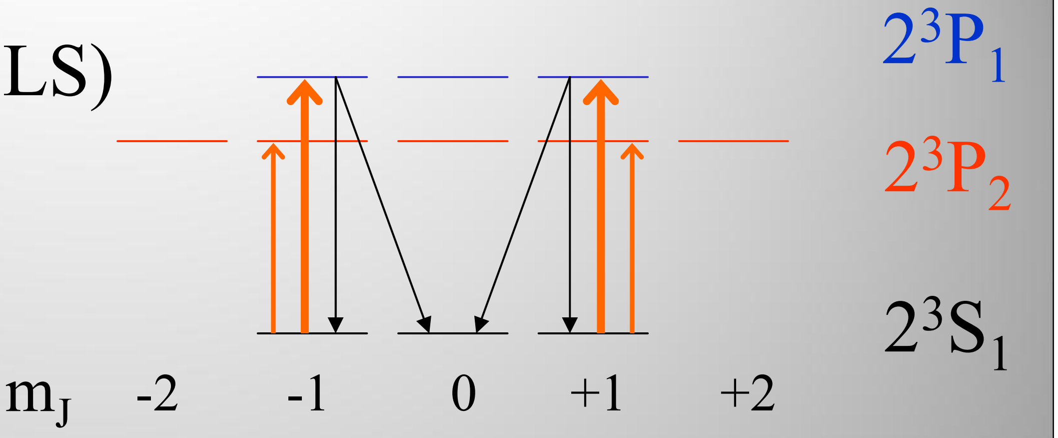
Perspectives for He precision spectroscopy…

- ***Frequency measurements of other optical He transitions at the 10^{-12} (or better) accuracy level***



Other systematical effects

- AC Stark shift (*light shift*, LS)



$LS \propto |\Omega|^2 / \delta$

- Doppler Shift

2nd order: ~15 kHz with $v = 3200\ \mathrm{m\ s^{-1}}$)

Simulation with RS, LS and 2nd DS

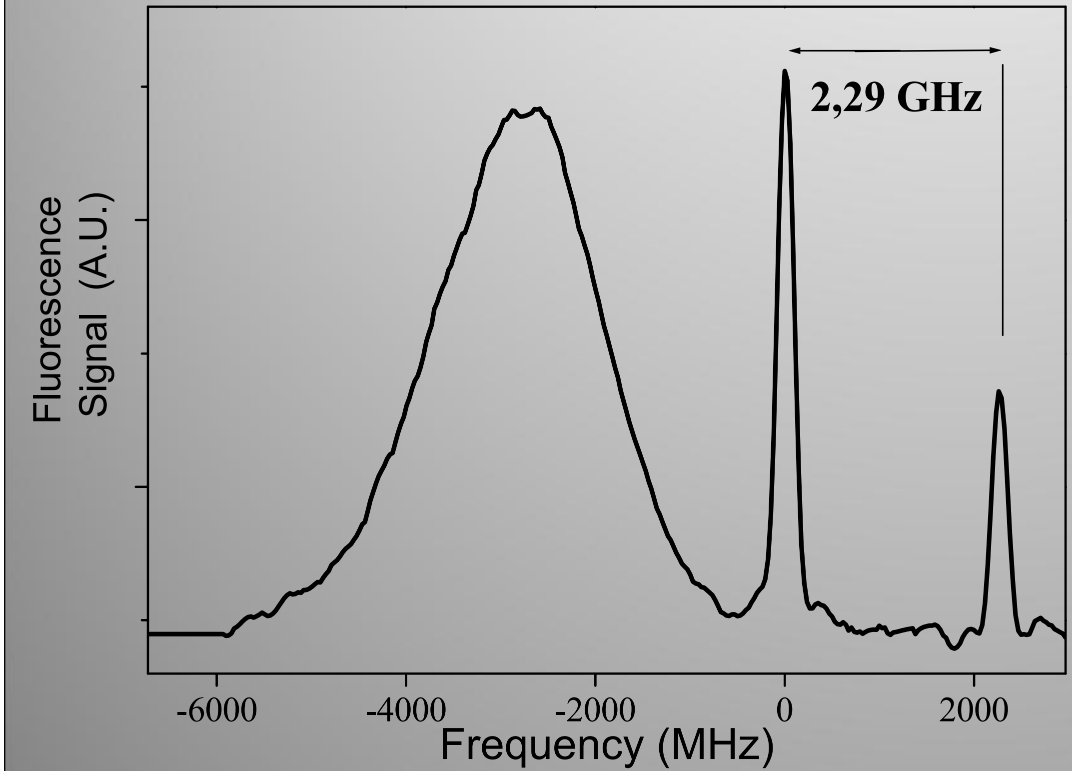
for 1→0 e 1→1 open transitions ~70 kHz and 80 kHz

for 1→2 closed transition ~240 kHz

Velocity distribution of atomic beam

generalized maxwellian:

$$n(v_z) = (v_z / a)^{b-1} \exp[-(v_z / a)^2]$$



$a \sim 1800$ m/s

$b \sim 6$

⬇

$\langle v \rangle \approx 3200$ m/s

Other systematical effects

- Doppler Shift

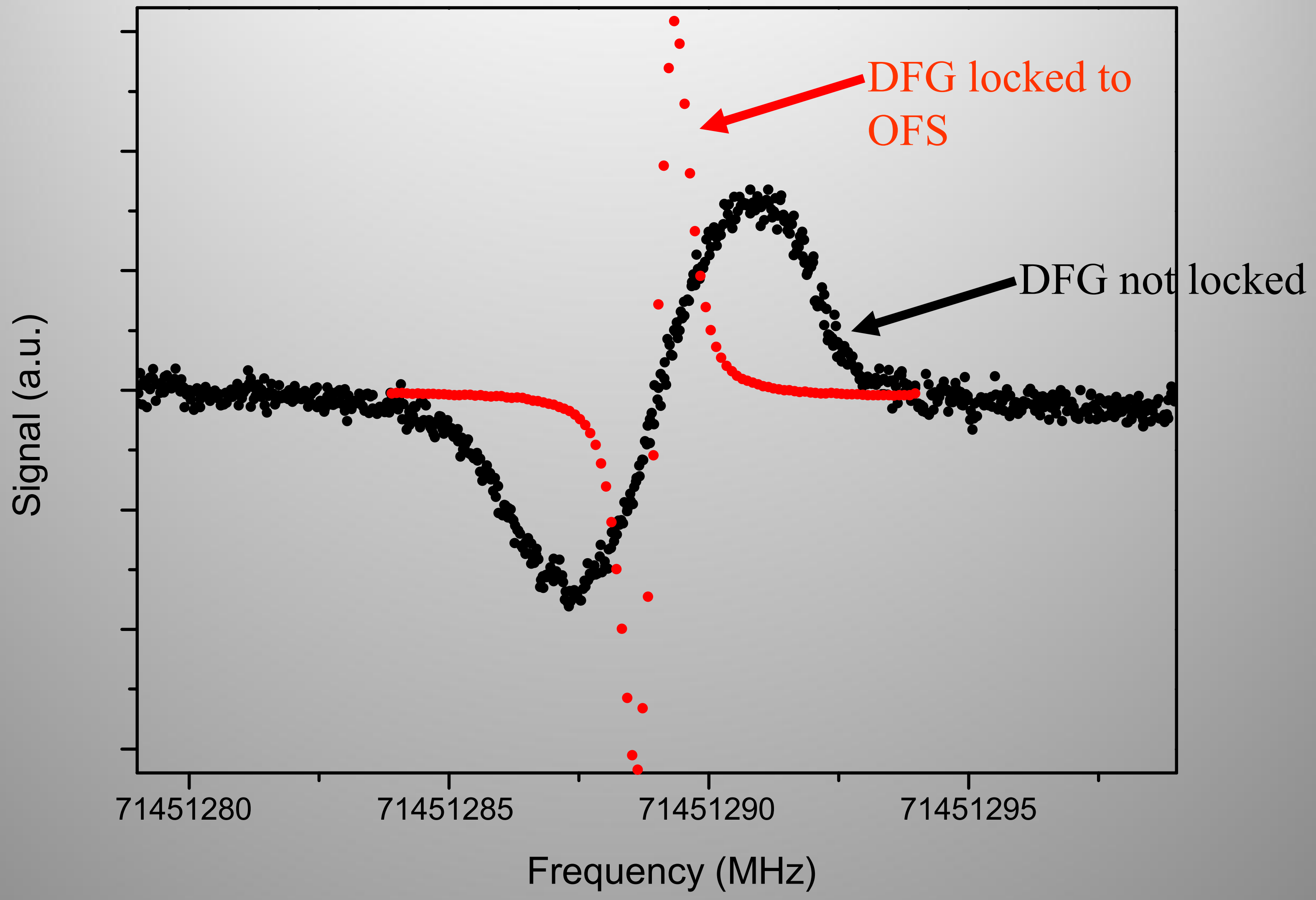
  1st order (residual): ~ 0.7 kHz

  due to misalignement of cat-eye system

- Zeeman shift (residual): < 0.1 kHz

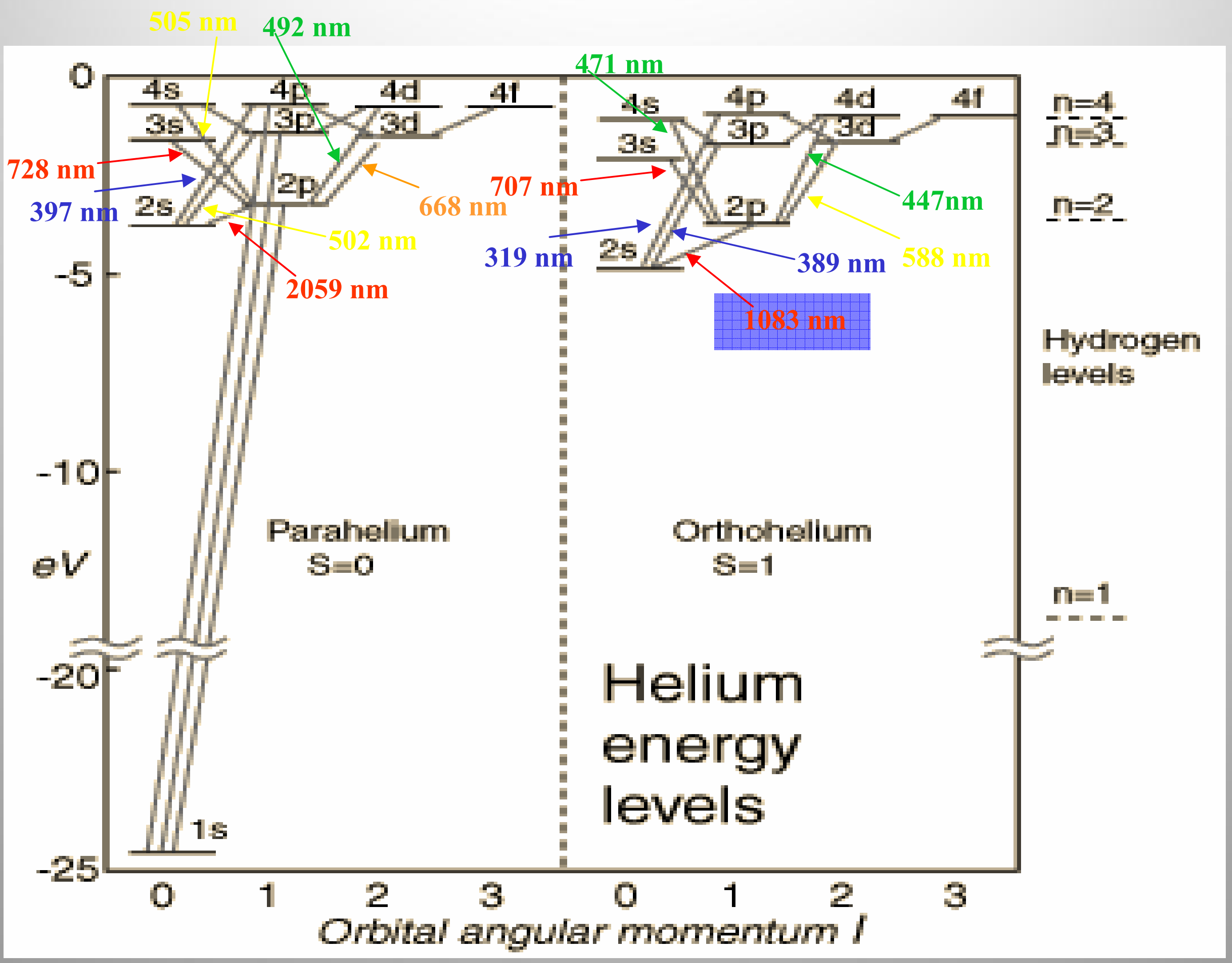
  μ-metal shield
  anti-helmoltz coils → magnetic field < 0.1 μT

Applied to the measurement of absolute frequencies of CO_2 ro-vibrational transitions at 4.25 µm



10^{-11} accuracy (at present, limited by linewidth and S/N)

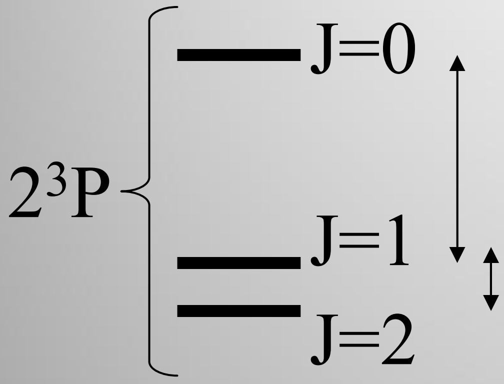
He transitions from Rydberg levels are in the visible-near IR



At present they can be measured with high precision (10^{-12}-10^{-15}) thanks to the Optical Frequency comb Synthesizer (OFS).

Fine structure of triplet P levels in ^{4}He

G. Giusfredi *et al.*, *Can. J. Phys.* **83**(4), 301-310 (2005)



$\nu_{01} \sim 29\,616.9$ MHz $\sim \alpha^2$

$\nu_{12} \sim 2\,291.2$ MHz

Determination of Fine Structure Constant

$$\nu_{01}\,(\text{meas.}) - \delta\nu_{01}(\text{QED}>\alpha^4) = \alpha^2 \times 556\,200\,289.5 \text{ MHz}$$

K. Pachucki and J. Sapirstein, *J. Phys. B.* **35**,1783 (2002)

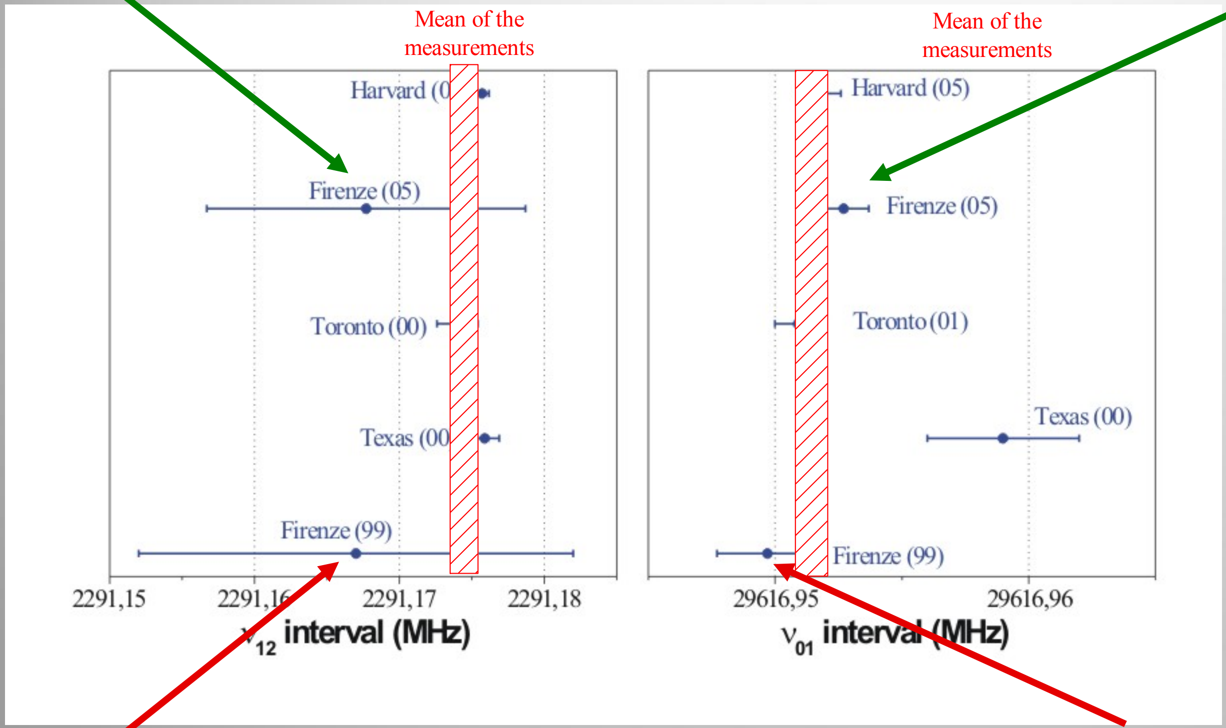
15ppb in α → 30ppb accuracy for ν_{01} (1 kHz) and $\delta\nu_{01}$

Present experimental situation

6 ppm

30 ppb

I_2 master reference



6 ppm

60 ppb

Firenze (99): PRL **82**, 1112 (1999)

Texas (00): PRL. **84**, 4321 (2000)

Toronto (00): PRL **84**, 3274 (2000)

Toronto (01): PRL. **87**, 173002-1 (2001)

Firenze (05): CJP **83**(4), 301 (2005)

Harvard (05): PRL **95**, 203001 (2005)

He master reference

Weighted-average values:

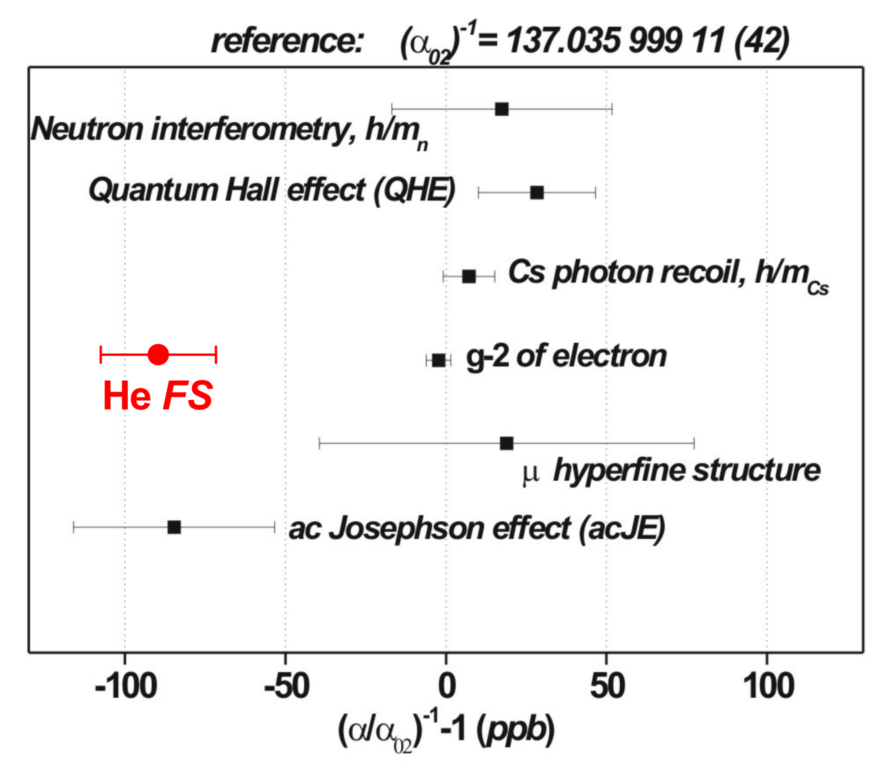
$$\nu_{12} = 2\ 291\ 174.9\ (9)\ \text{kHz}\ (400\ \text{ppb})$$

$$\nu_{01} = 29\ 616\ 951.7\ (6)\ \text{kHz}\ (20\ \text{ppb})$$

Implications in α determination

From weighted-average ν_{01}(exp.) = 29 616.951 7 (6) MHz
and from recent calculation $\delta\nu_{01}$= -1.47213(50) MHz

$$\alpha^{-1}_{\mathrm{HeFS}} = 137.\,035\,9873(18) \quad (13\mathrm{ppb})$$



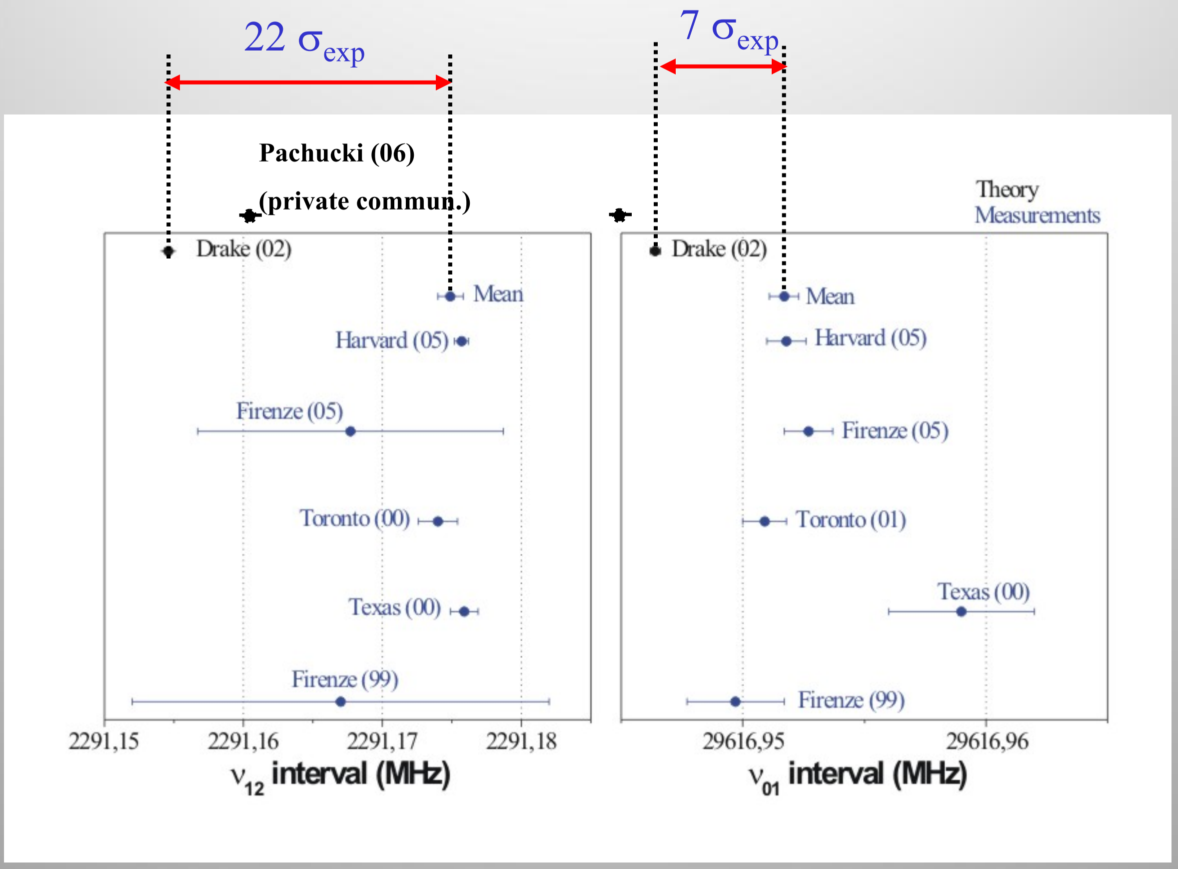
but…

$$\alpha^{-1}_{\mathrm{HeFS}} - \alpha^{-1}_{02} =$$

-90.9 ppb ($\approx 7\,\sigma$!!!)

Implications in α determination

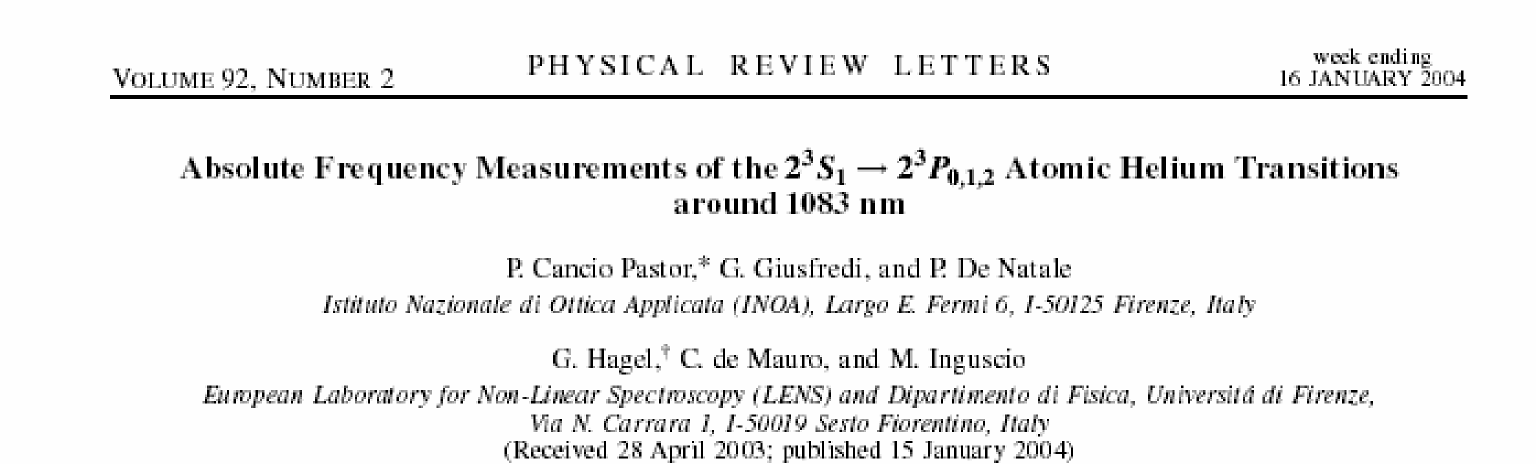
Problem: - discrepancy between theory and experiment (larger for ν_{12})



Conclusion:

FS He measurements are a test of the He QED theory

"center of gravity" of $2^3S \rightarrow 2^3P$ transition



VOLUME 92, NUMBER 2 PHYSICAL REVIEW LETTERS week ending 16 JANUARY 2004

Absolute Frequency Measurements of the $2^3S_1 \rightarrow 2^3P_{0,1,2}$ Atomic Helium Transitions around 1083 nm

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(Received 28 April 2003; published 15 January 2004)

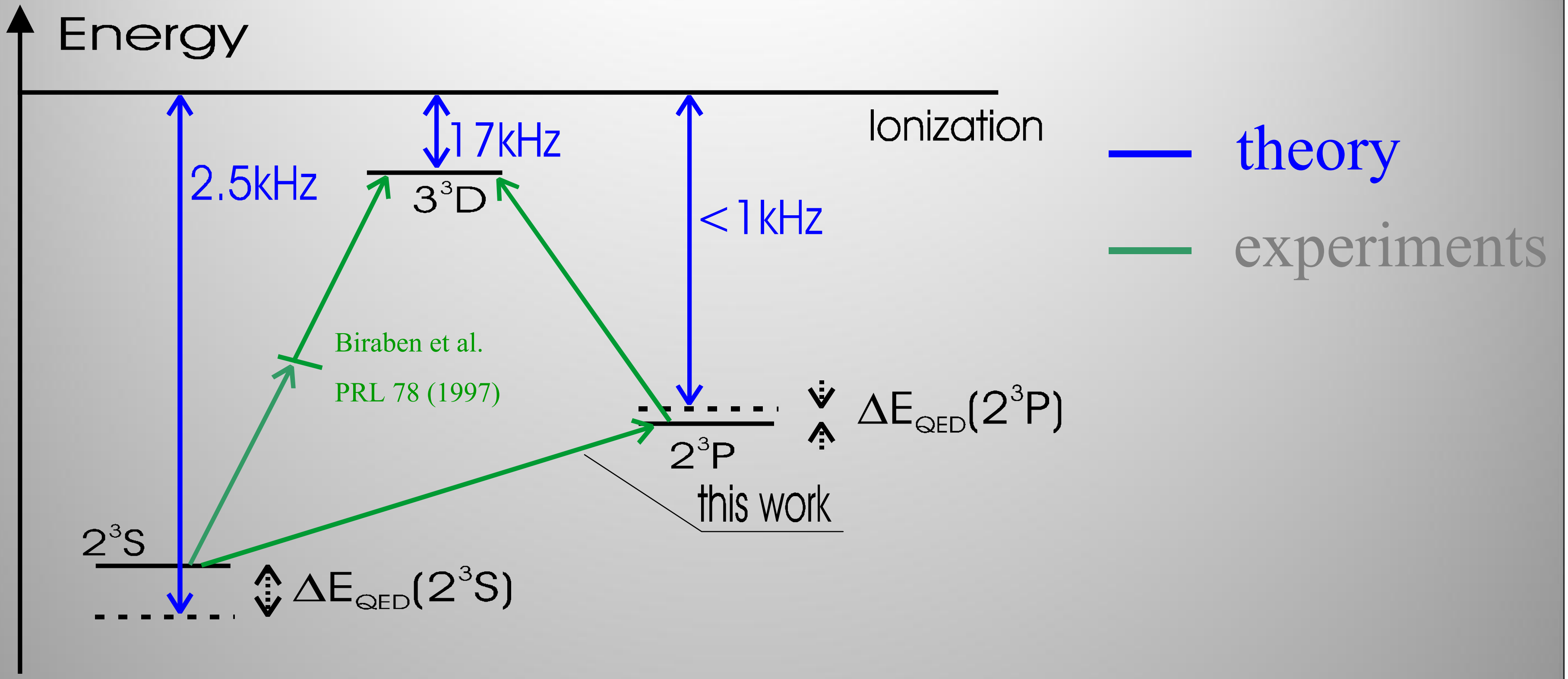
276 736 495 650.6(2.4) kHz

8.7×10^{-12} (30 times better)

Wavelength measurement: 276 736 495 580(70) kHz

D. Shiner *et al.*, PRL **72**, 1802 (1994)

Lamb Shifts determinations



$$\Delta E_{QED}(2^3P) = -1\,253.975(58)\ \text{MHz}$$

precision
2 times better

$$\Delta E_{QED}(2^3S\text{-}2^3P) = 5\,311.2134(31)\ \text{MHz}$$

best determination for
a Lamb Shift in Hydrogen
or Helium (6.6×10^{-7})

Isotope shift ^{3}He-^{4}He

$$\Delta\nu_{IS} = \nu_3 - \nu_4 = \Delta\nu_{MS} + \Delta\nu_{VS}$$

For He $\Delta\nu_{MS} \gg \Delta\nu_{VS}$

$2\,^3S \rightarrow 2\,^3P$ ~ 33.7 GHz ~1.3 MHz

$$\Delta\nu_{VS} = \nu_{VS,3} - \nu_{VS,4} \Longrightarrow \frac{\delta(\nu_{VS,3})}{\nu_{VS,3}} = 2\frac{\delta(R_3)}{R_3}$$

$\nu_{VS,3}$ ~ 4.7 MHz

$\delta(R_3)/R_3 \sim 6\times10^{-4}$

⇓

$\delta(\nu_{VS,3})$ ~ 5 kHz

⇓

0.1ppm for $\Delta\nu_{IS}$ and $\Delta\nu_{MS}$

⇓

10^{-11} for ν_3 and ν_4

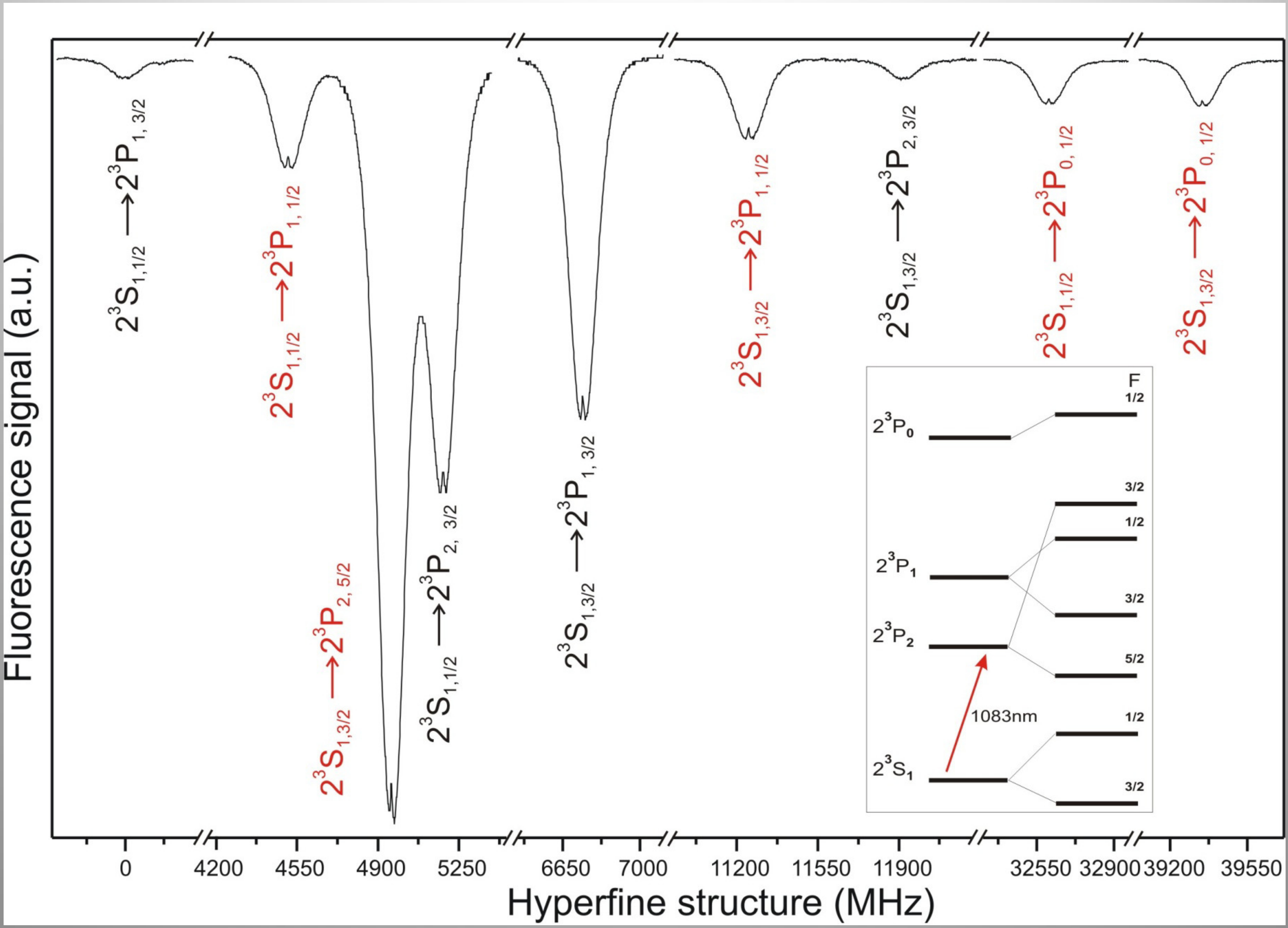
$$\text{Measurement} \longleftarrow \Delta\nu_{IS} = \overbrace{\Delta\nu_{MS} + \left(C_3 \boxed{R_3^2} - C_4 R_4^2\right)}^{\text{Theory}}$$

Known at 6×10^{-4} (1.673(1) fm)

Nuclear charge radius determination

- Test the Standard Nuclear Structure Model;
- Study nucleon interactions in neutron-rich matter.

Hyperfine ^{3}He transitions at 1083 nm



^{3}He gas-recirculation system was implemented → **simultaneous ^{3}He and ^{4}He measurements**