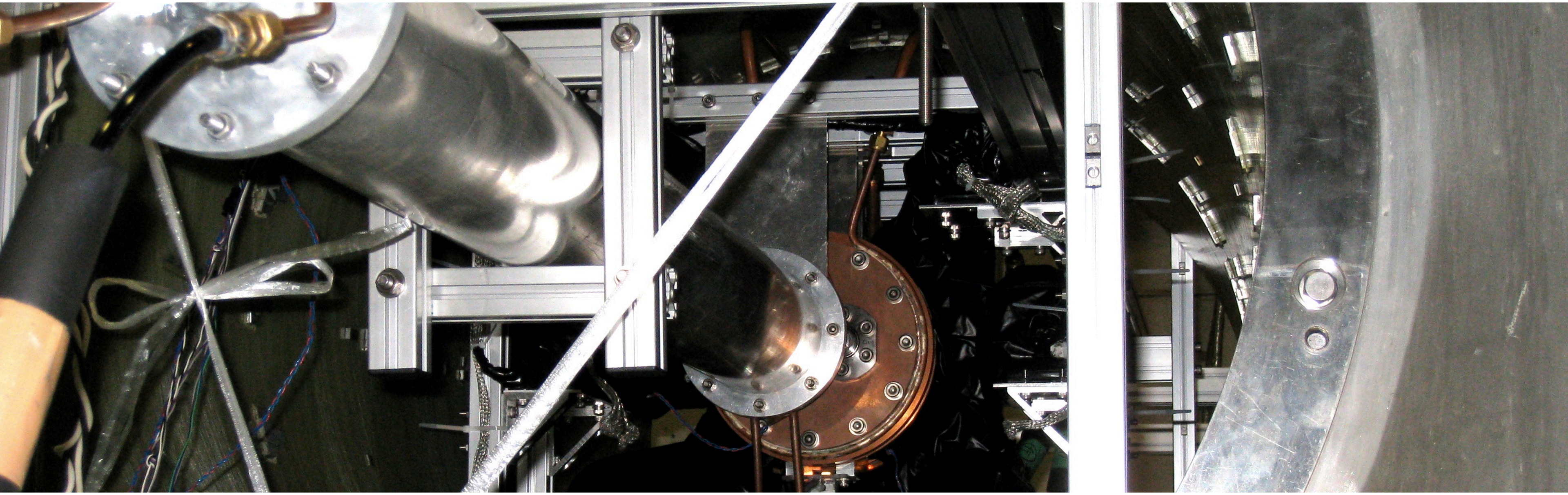
Precision measurement of the hyperfine splitting of positronium



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International Conference on Precision Physics and Fundamental Physical Constants (FFK-2015)

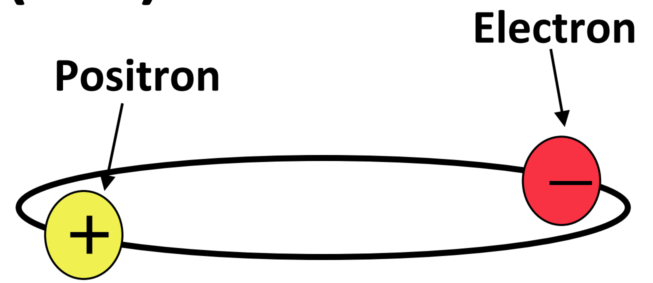
12/10/2015 Hungarian Academy of Sciences, Budapest, Hungary

Outline

- Introduction: Positronium Hyperfine Splitting (Ps-HFS) *puzzle*
- Ps thermalization effect on Ps-HFS
- New Experiment
- Future Prospects
- Other new approaches
- Conclusion

Positronium (Ps)

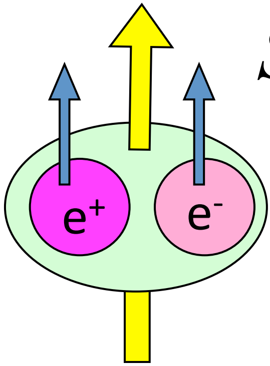
Bound state of an electron (e^-) and a positron (e^+)



Lightest and Exotic Atom

- Lightest hydrogen-like atom (mass = 1.022 MeV)
- Pure leptonic system. Free from uncertainties of hadronic interactions.
  -> Ideal system for precision test of bound-state Quantum ElectroDynamics (QED).
- Particle-antiparticle system
  -> Sensitive to physics beyond standard model.
- The lowest energy $e^+ e^-$ "collider"

Positronium (Ps)



$\vec{S}$ = 1 (Triplet)

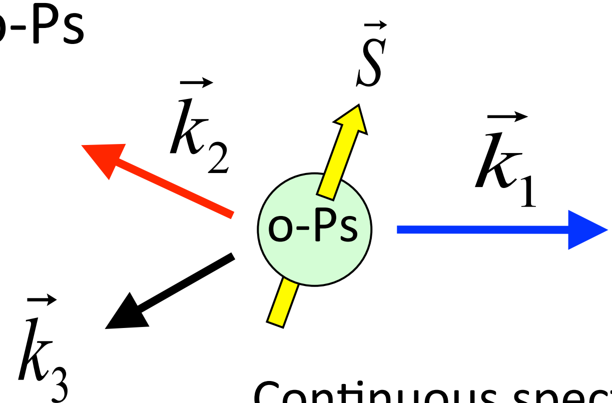
Ortho-positronium (o-Ps)

Spin=1 The same quantum number as photon

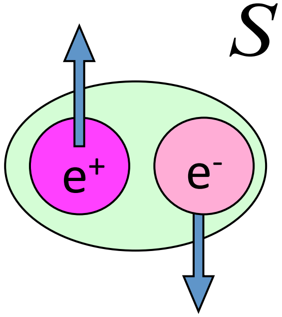
o-Ps → 3γ (, 5γ, …)

o-Ps

Lifetime 142 ns



Continuous spectrum



$\vec{S}$ = 0 (Singlet)

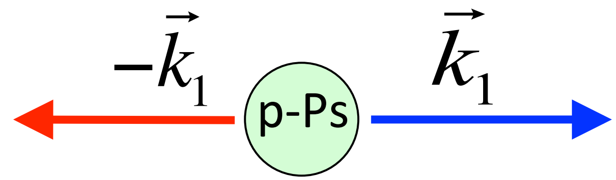
Para-positronium (p-Ps)

Spin=0 pseudo-scalar

p-Ps → 2γ (, 4γ, …)

p-Ps

Lifetime 125 ps



Monochromatic 511 keV

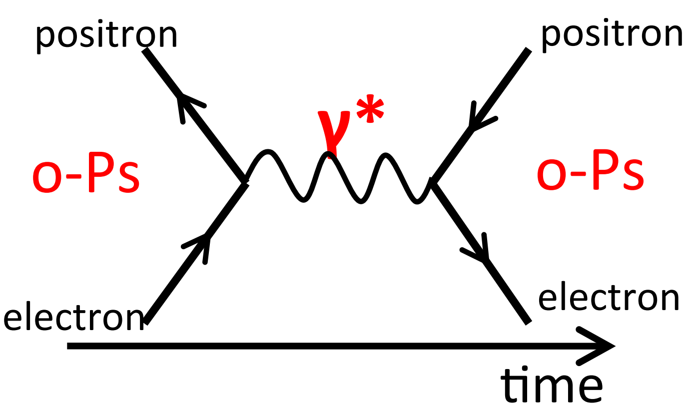
Positronium Hyperfine Splitting (Ps-HFS) and its characteristics

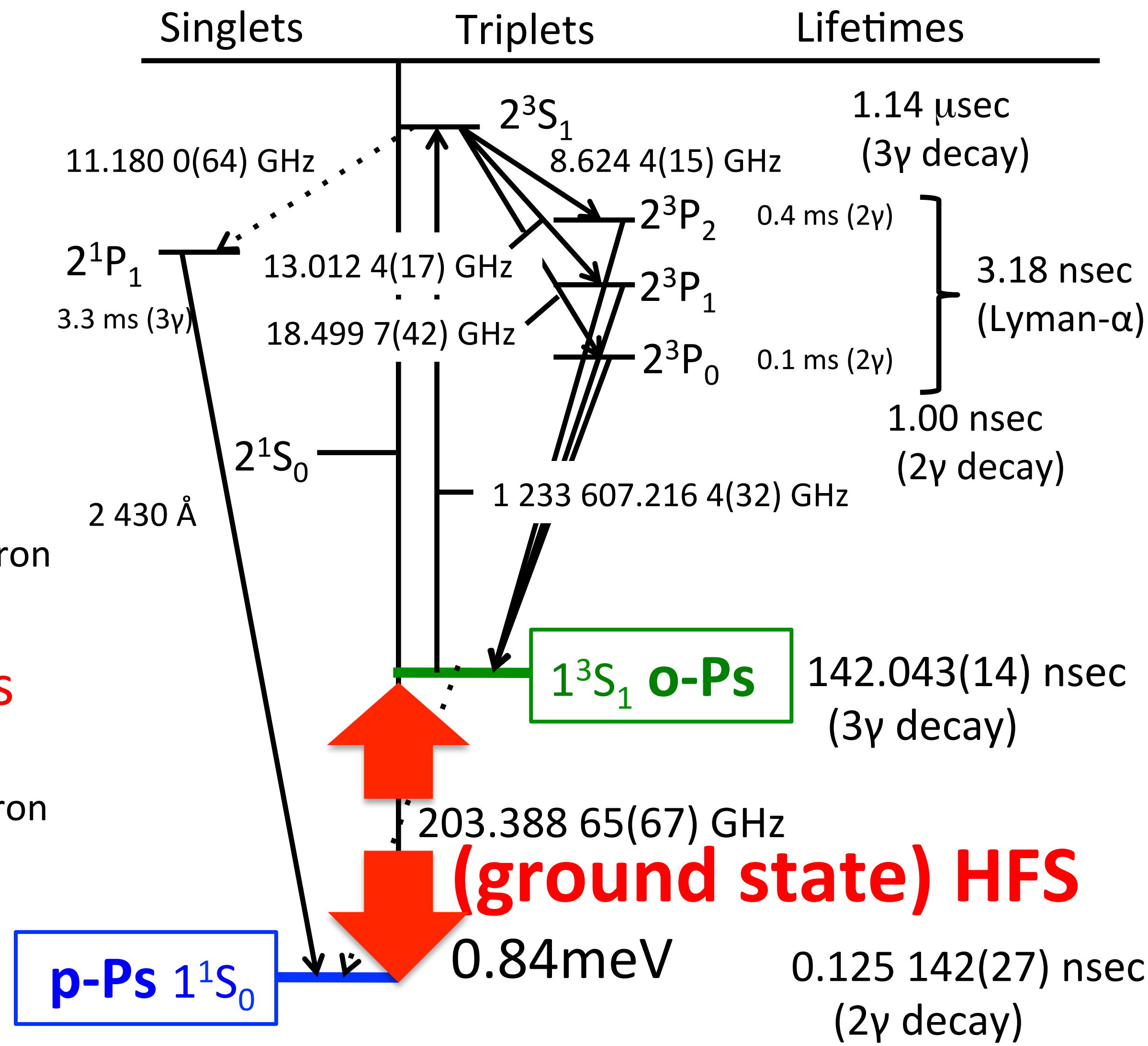
Energy difference between two spin eigenstates of the ground state Ps

→ Ps-HFS (203 GHz)

$$\mu = \frac{e}{2m}\sigma$$

spin-spin interaction





Quantum oscillation effect is also large (40%)

→ Sensitive to new physics beyond SM

History of Ps-HFS

Experiment

- First measurement by M. Deutsch and S.C. Brown (1952, 1500 ppm).
- Most precise measurements by two independent groups:
  A.P. Mills, Jr. and G.H. Bearman (1975 and 1983, 8 ppm),
  M.W. Ritter, P.O. Egan, V.W. Hughes, and K.A. Woodle (1984, 3.6 ppm).
- Our new precise measurement taking into account the Ps thermalization effect (A. Ishida *et al.*, 2014, 10 ppm).

Theory

Pure
bound-state QED

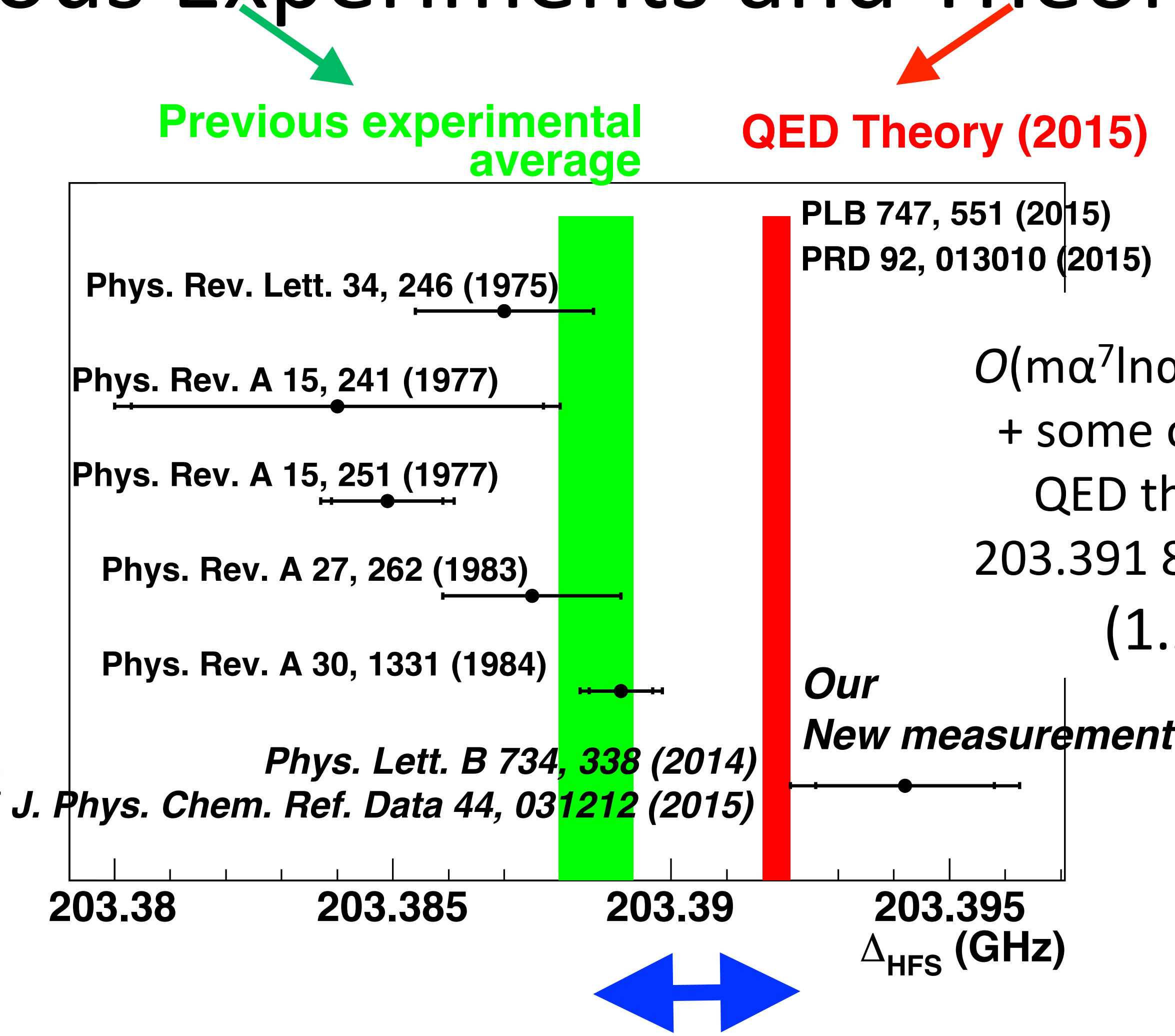
$$\Delta_{\mathrm{HFS}}^{\mathrm{th}} = \frac{7}{12} m_e \alpha^4 \left\{ 1 - \frac{\alpha}{\pi}\left(\frac{32}{21} + \frac{6}{7}\ln 2\right) + \frac{5}{14}\alpha^2 \ln\frac{1}{\alpha} + \left(\frac{\alpha}{\pi}\right)^2 \left[\frac{1367}{378} - \frac{5197}{2016}\pi^2 + \left(\frac{6}{7} + \frac{221}{84}\pi^2\right)\ln 2 - \frac{159}{56}\zeta(3)\right] - \frac{3}{2}\frac{\alpha^3}{\pi}\ln^2\frac{1}{\alpha} + \left(\frac{62}{15} - \frac{68}{7}\ln 2\right)\frac{\alpha^3}{\pi}\ln\frac{1}{\alpha} + D\left(\frac{\alpha}{\pi}\right)^3 + \ldots \right\},$$

- First term calculated by three groups (1947-1951).
- $O(m\alpha^7 \ln(1/\alpha))$ was calculated by three groups (2000-2001).
- $O(m\alpha^7)$ non-logarithmic term calculation are ongoing since 2014, motivated by our experimental result and many other efforts.

Ps-HFS Puzzle: Discrepancy Between Previous Experiments and Theory

Previous experimental results are consistently lower than theory.

Previous experimental average
203.388 65(67) GHz
(3.3 ppm)

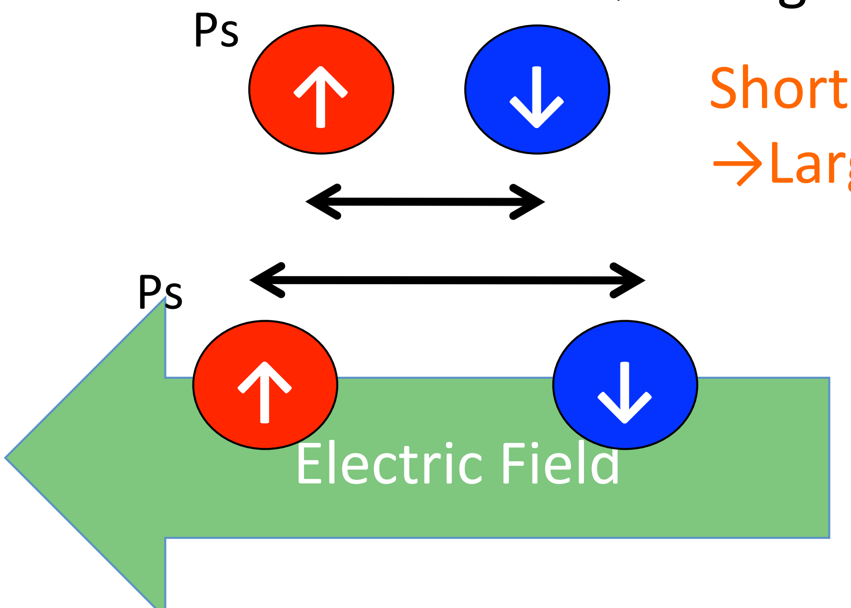


$O(m\alpha^7 \ln\alpha^{-1})$
+ some of $O(m\alpha^7)$
QED theory
203.391 89(25) GHz
(1.2 ppm)

16 ppm (4.5 σ) significant discrepancy

Material Effect on Ps-HFS

- Need material (in this case gas molecules) so that positron can get electron and form Ps.
- Ps-HFS
  = Spin-spin interaction + quantum oscillation
  →Depends the distance between e^- and e^+.
- Materials make electric field around Ps
  →Change the distance of the electron and the positron
  →Change HFS（The Stark Effect）



Short distance
→Large HFS

Long distance
→Difficult to interact
→Small HFS

Estimation of Material Effect in previous experiments

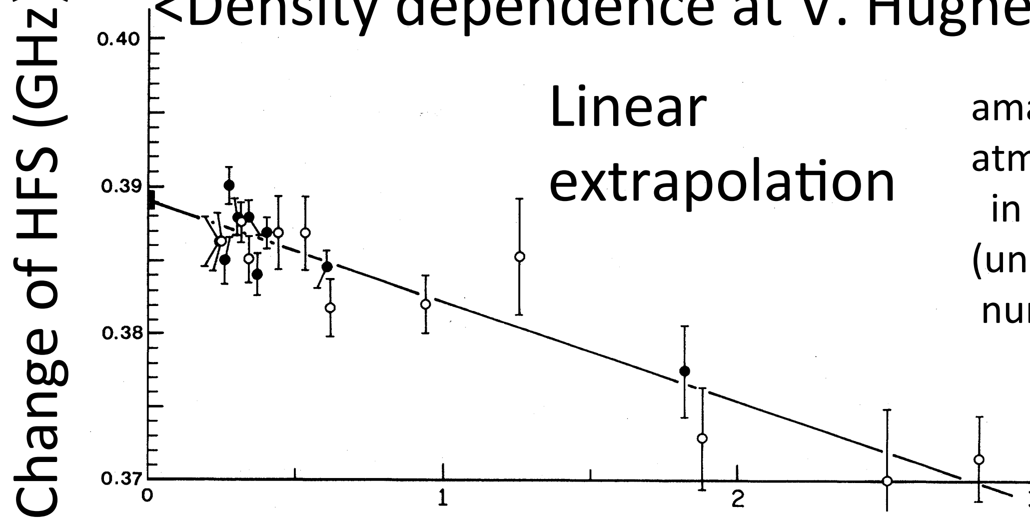
- Need material (gas molecules) so that positron can be cooled down, and form Ps → Ps feels electric field of molecules

Strength of the Stark Effect
(∝ ~ Collision rate with surrounding molecules)
∝ (Density of surrounding molecules) x (Ps velocity v)$^{3/5}$

→If the Ps velocity is constant (under assumption that Ps is well thermalized), the material effect is proportional to gas density.

→The Previous experiments

<Density dependence at V. Hughes *et al.*>



amagat = atm @ 0 ^{O}C in ideal gas (unit of number density)

N_2 gas density (amagat)

Phys. Rev. A
1984 **30** 1331
Ritter, Egan, Hughes et al.

FIG. 7. Measured values of $\Delta\nu$ vs ... n circles are from Ps IV and the closed circles are from the present work. The straight line is the best fit described in Eq. (14).

Ps thermalization and its effect on Ps-HFS

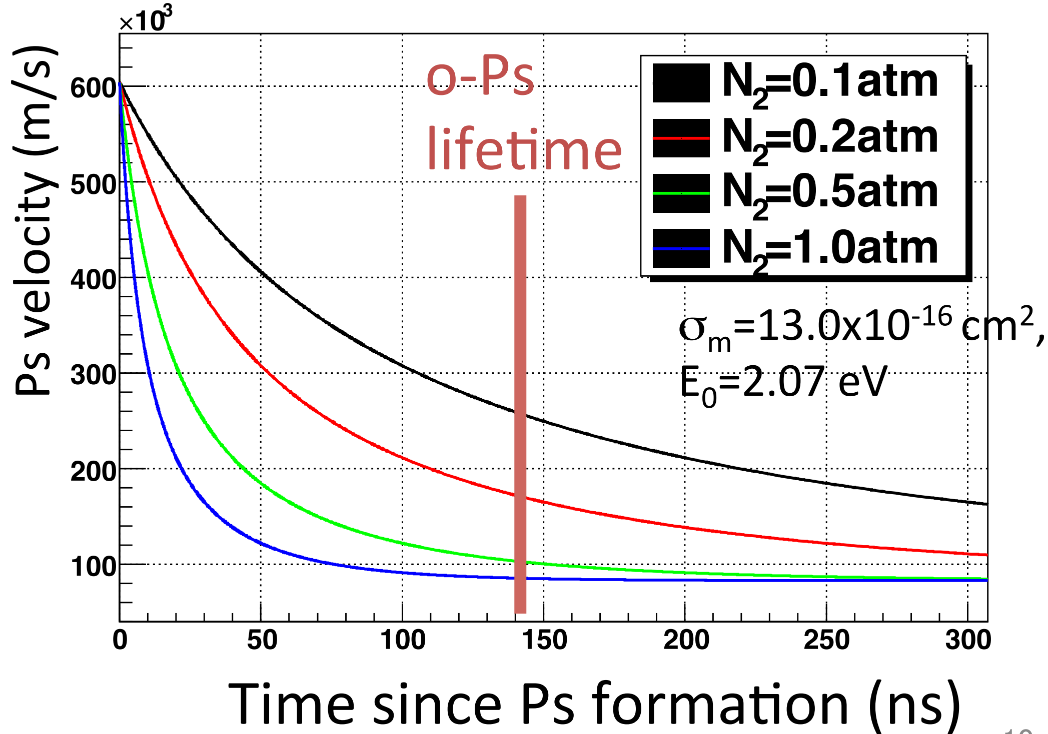
Strength of the Stark Effect
(∝ ~ Collision rate with surrounding molecules)
∝ (Density of molecules) x (Ps velocity v(t))$^{3/5}$

Ps loses its kinetic energy and gets room temperature = Thermalization

It takes longer time to thermalize in lower density
→ Linear extrapolation could be a large systematic uncertainty

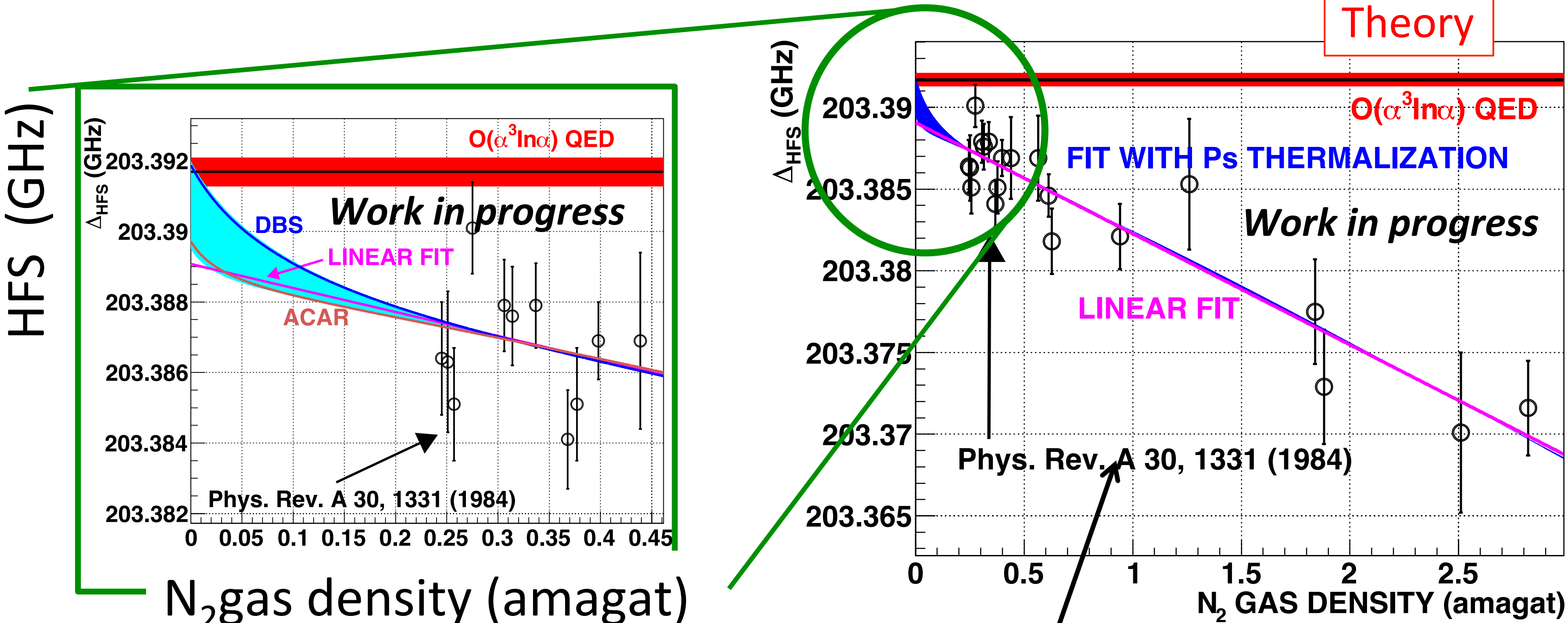
→Ps thermalization should be carefully treated in Ps-HFS measurement.

< Simulation of time evolution of Ps velocity in N_2 gas >



Ps thermalization effect on Ps-HFS

<Simulation of material effect correction from density + thermaliaztion.
Time evolution of Ps-HFS has not been taken into account.>



O(10 ppm) correction in N_2 case:

- Put the experimental value close to the theory.
- Significant correction which cannot be ignored.
- Different techniques give different corrections.
  - →Main reason of large uncertainty
  - →**Measured the thermalization independently.**

(σ_m, E_0)=
DBS:(13.0×10^{-16} cm^2 , 2.07 eV)
ACAR:(37×10^{-16} cm^2 , 2.07 eV)
RF frequency = 2.32 GHz
RF magnetic field =10 Gauss
Static magnetic field = 0.78 Tesla
Experiment: Hughes et al. (1984)
Theory: Kniehl et al. (2000)

Our New Experiment

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High Energy Accelerator Research Organization (KEK)

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KEK CSC

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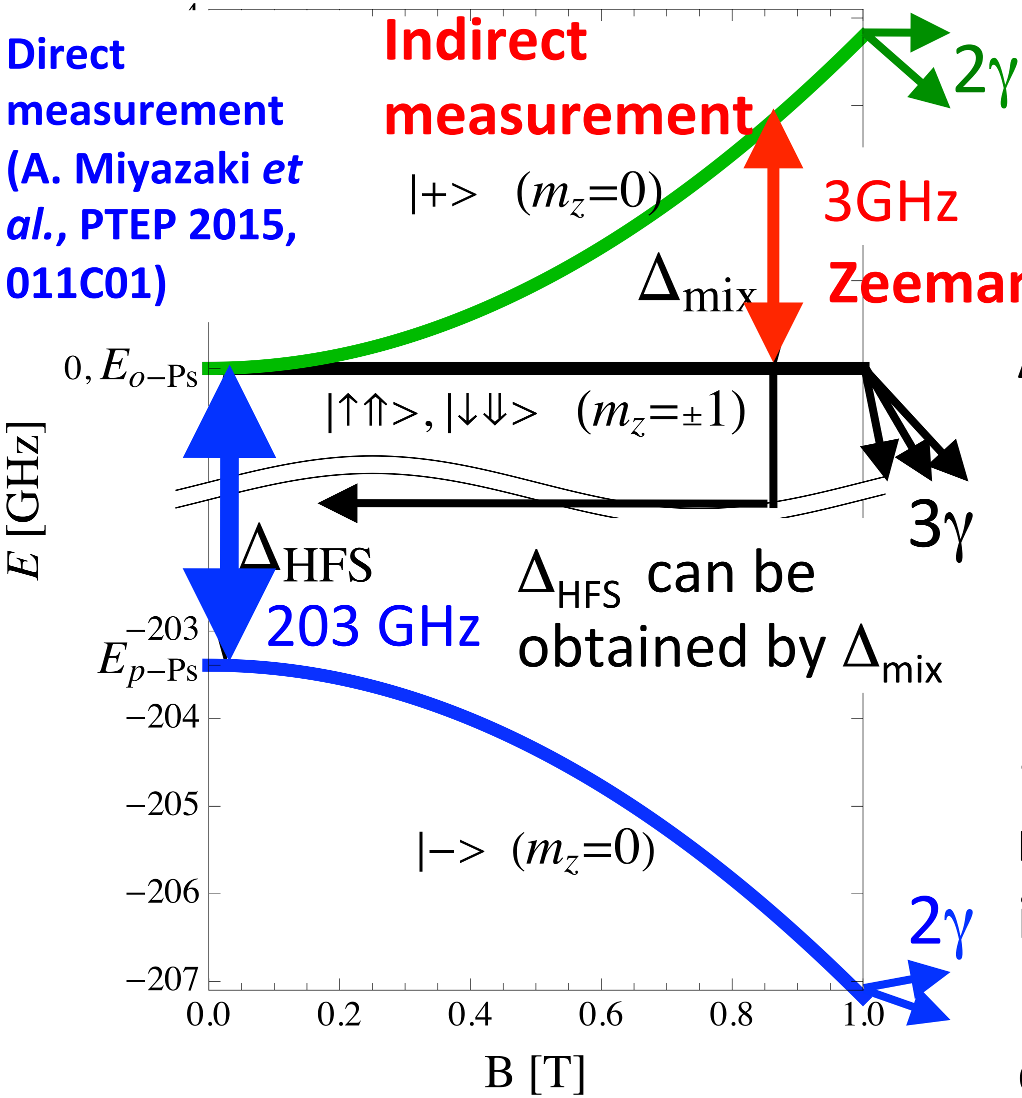
PHYSICS LETTERS B

New precision measurement of hyperfine splitting of positronium

CrossMark

A. Ishida [a,*], T. Namba [a], S. Asai [a], T. Kobayashi [a], H. Saito [b], M. Yoshida [c], K. Tanaka [c], A. Yamamoto [c]

Experimental technique: Indirect Measurement using Zeeman Effect



In a static magnetic field, the **p-Ps** state mixes with the **m_z=0 state of o-Ps** (Zeeman effect).

Approximately,

$$\Delta_{mix} \approx \frac{1}{2}\Delta_{HFS}\left(\sqrt{1+4x^2}-1\right),$$

$$x = \frac{g'\mu_B B}{h\Delta_{HFS}}.$$

This is not precise enough, so we solve time evolution of density matrix.

→ 2γ-ray annihilation (**511 keV monochromatic signal**) rate increases.

This increase is our experimental signal.

Used new techniques to reduce the possible reasons of the puzzle

Two possible common systematic uncertainties in the previous experiments

1. Non-uniformity of the magnetic field.
2. Underestimation of material effects. Unthermalized o-Ps effect can be significant

cf. o-Ps lifetime puzzle (1990's)

New techniques were introduced to reduce these uncertainties.

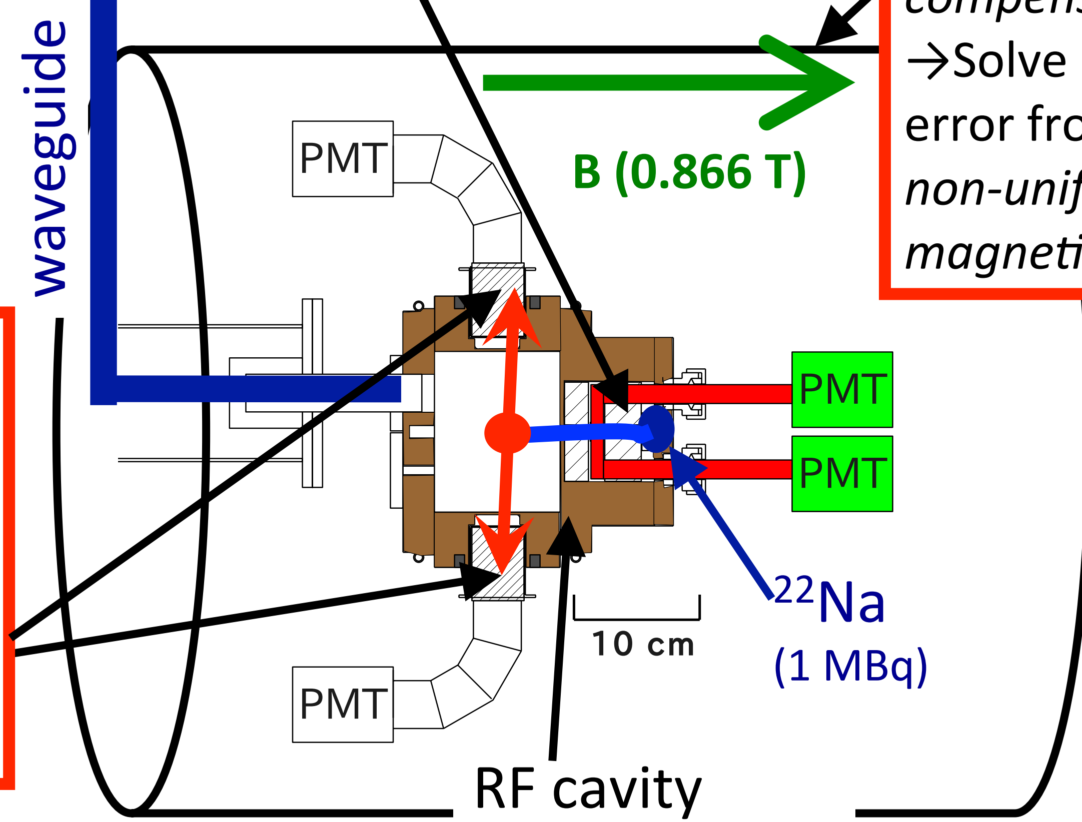
- Large-bore superconducting magnet to reduce the uncertainty 1.
- Time information (by β-tagging system and high-performance γ-ray detectors) to reduce the uncertainty 2.

Our New Experimental Setup

High power RF
(500W CW)

2 *β-tagging system*
→Solve systematic error
from *non-thermalized Ps*.

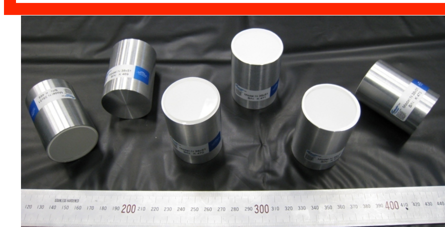
1 *Large bore superconducting magnet + compensation coils*
→Solve systematic error from *non-uniformity of magnetic field*.



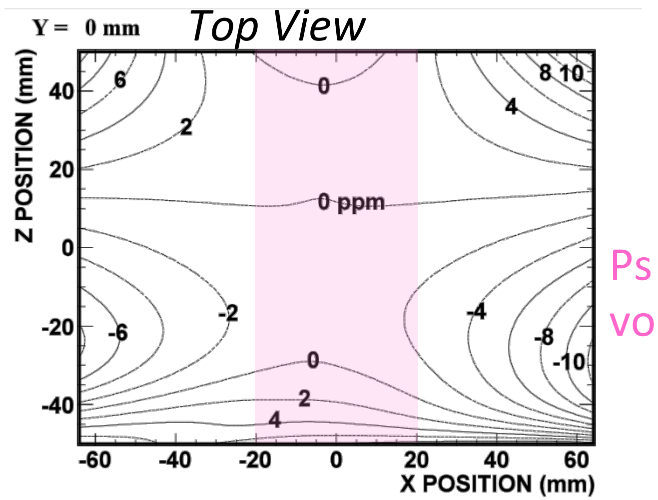
RF cavity
(Filled with
pure *i*-C_4H_{10})

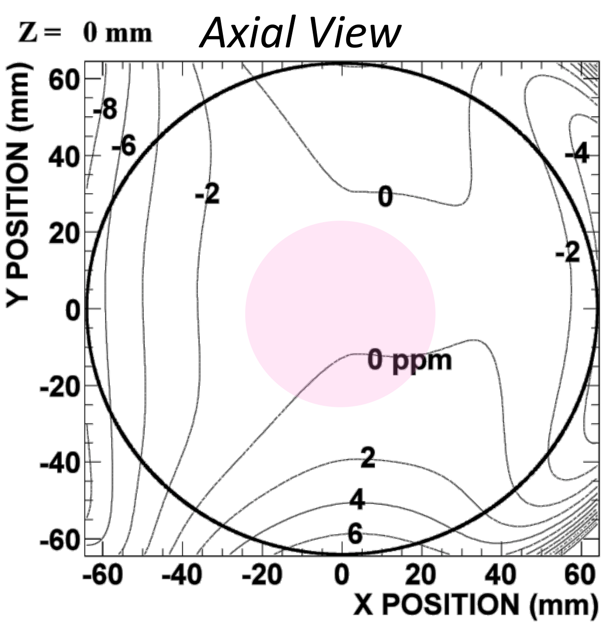
2 *High performance γ-ray detectors*
($LaBr_3$ scintillators)

→Solve systematic error from *non-thermalized Ps*.

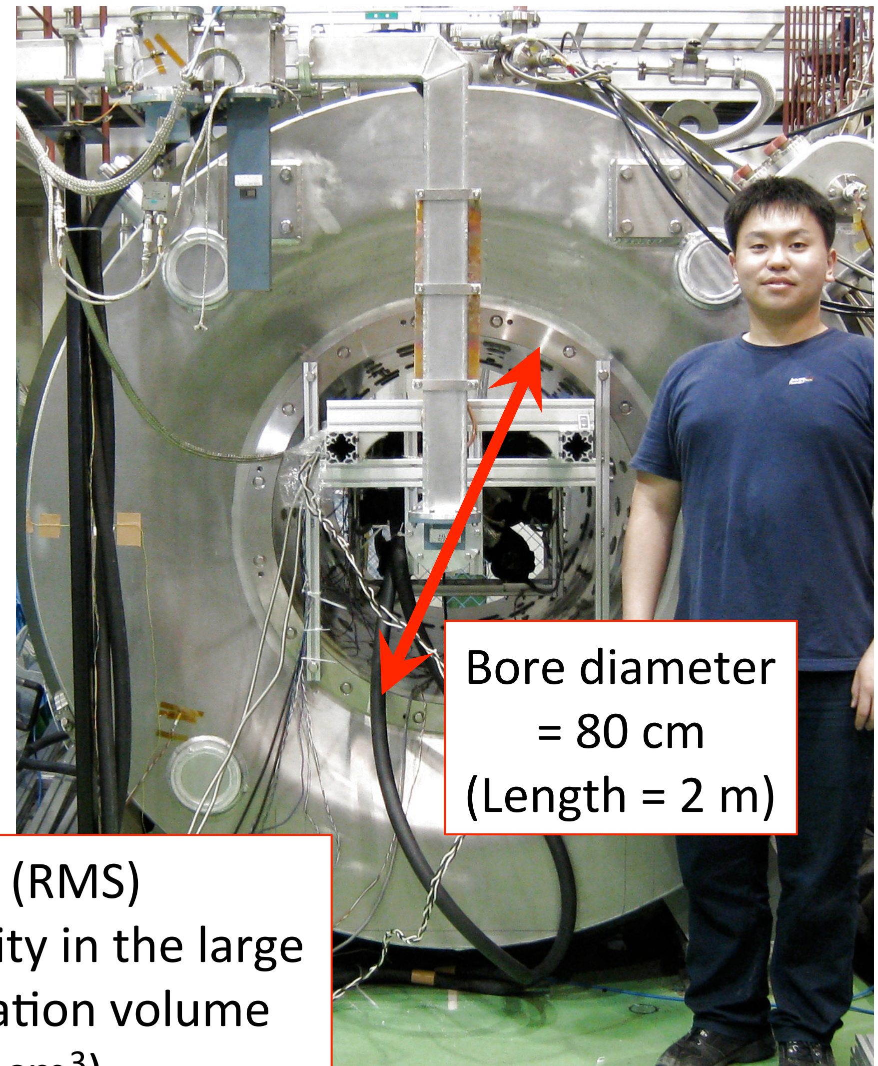


New technique 1: Large-bore superconducting magnet





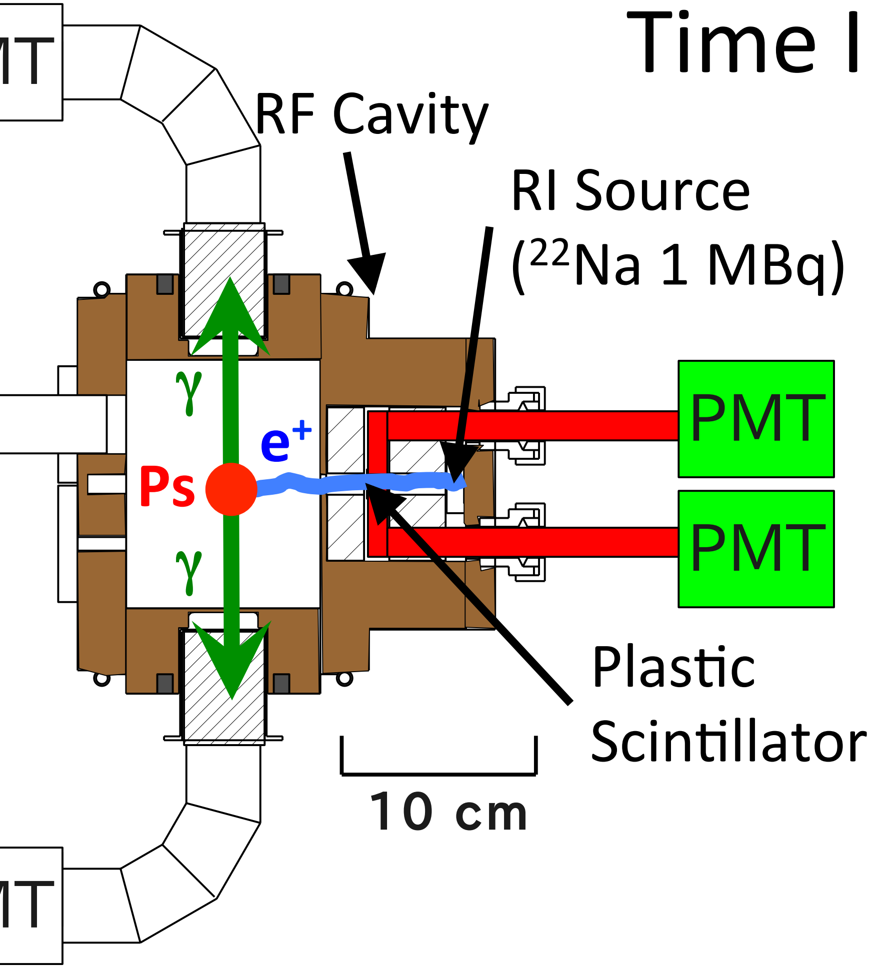
Ps formation volume



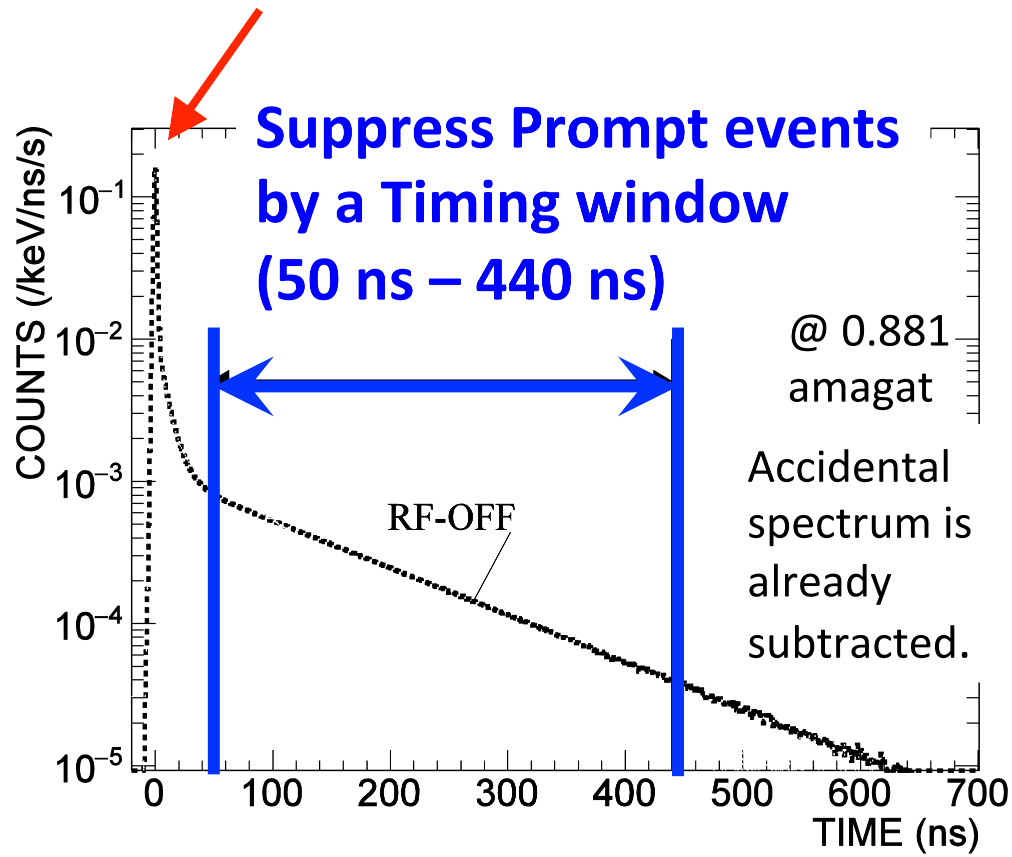
Bore diameter = 80 cm (Length = 2 m)

1.5 ppm (RMS) uniformity in the large Ps formation volume (~ 100 cm^3).

New technique 2:
Time Information



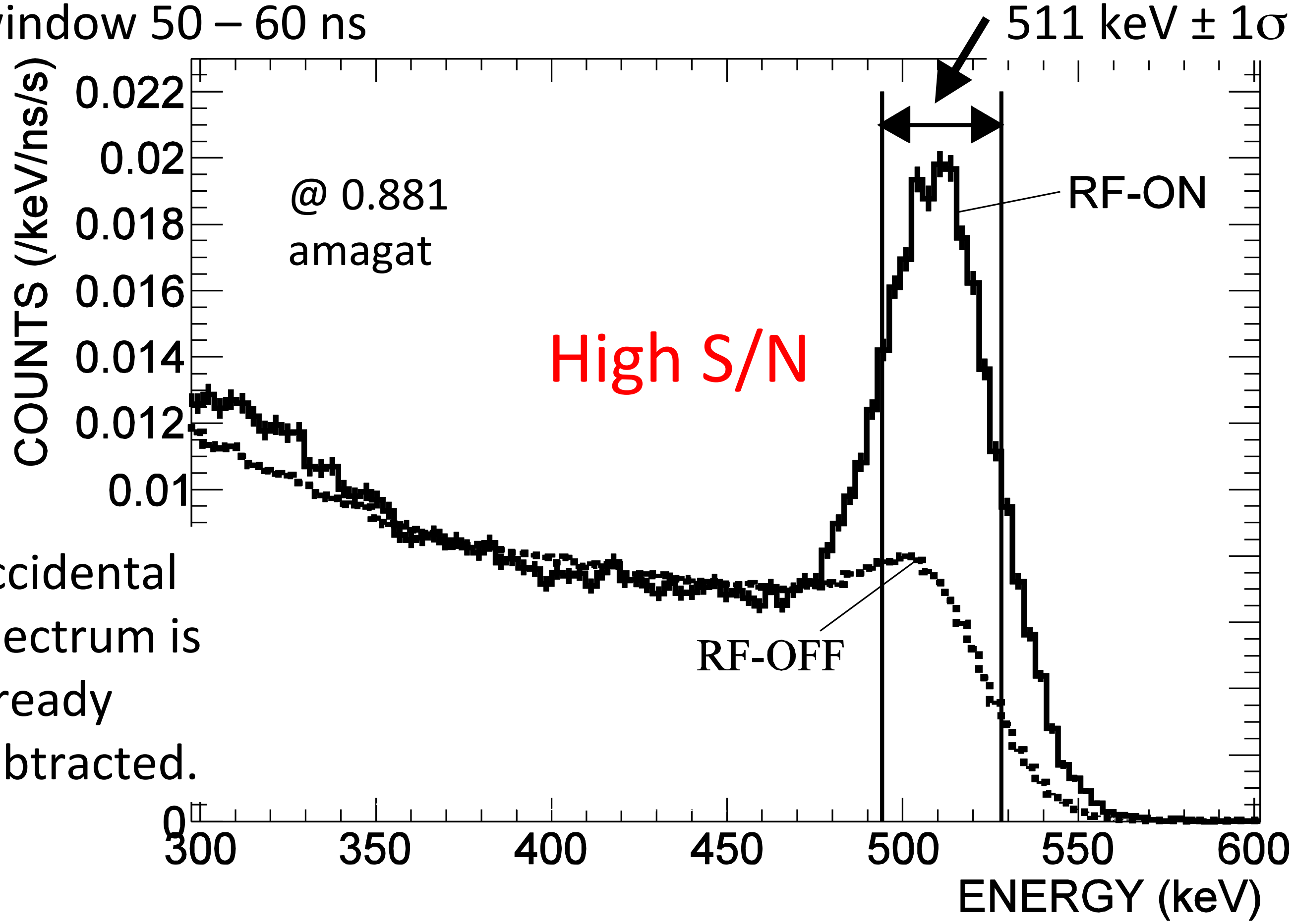
- Tag e^+ from the ^{22}Na by thin (0.1 mm) plastic scintillator.
  → *t=0*



- **Treat Ps thermalization correctly**
- **20 times higher S/N**

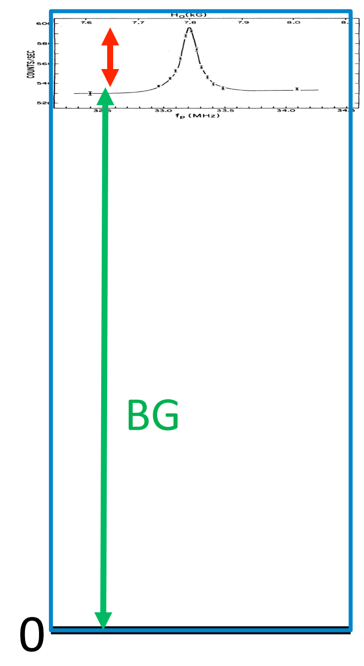
Comparison of energy spectra (RF-ON/OFF)

timing window 50 – 60 ns



Accidental spectrum is already subtracted.

cf. S/N of previous experiment

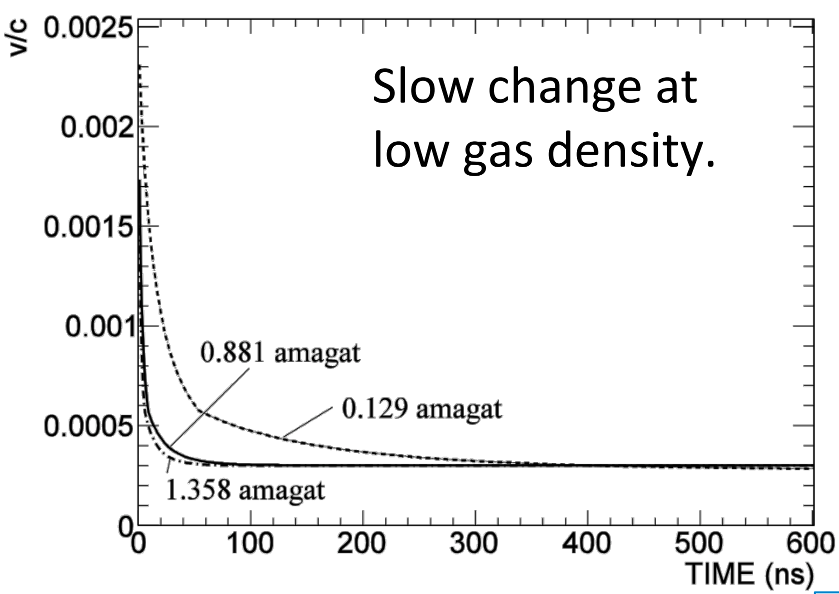


2γ decay rate increases because of the Zeeman transition. Use (RF-ON ー RF-OFF) / RF-OFF of count rates in the 511 keV ± 1σ energy window.

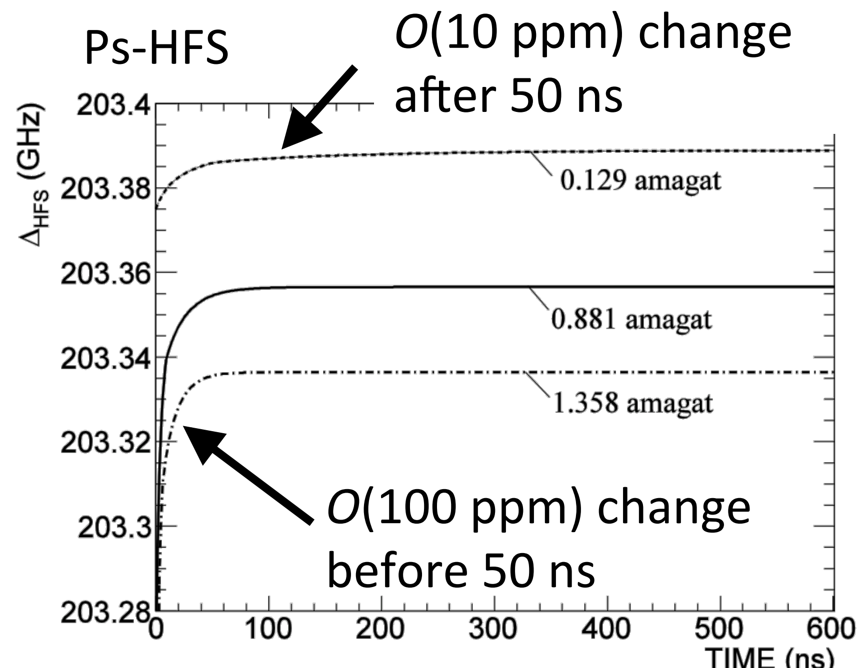
Fitting of resonance lines taking into account time evolution of Ps-HFS

- Scanned by Magnetic Field with the fixed RF frequency and power.
- 50—440 ns was divided to 11 sub timing windows.
- Simultaneous fit of all of the gas density, magnetic field strength, and (sub) timing windows.
- Time evolution of Ps velocity (thermalization) and Δ_{HFS} ($\propto nv^{3/5}$) were taken into account (Thanks to Prof. A. P. Mills, Jr. (UC Riverside) for useful discussions)

Ps velocity / c

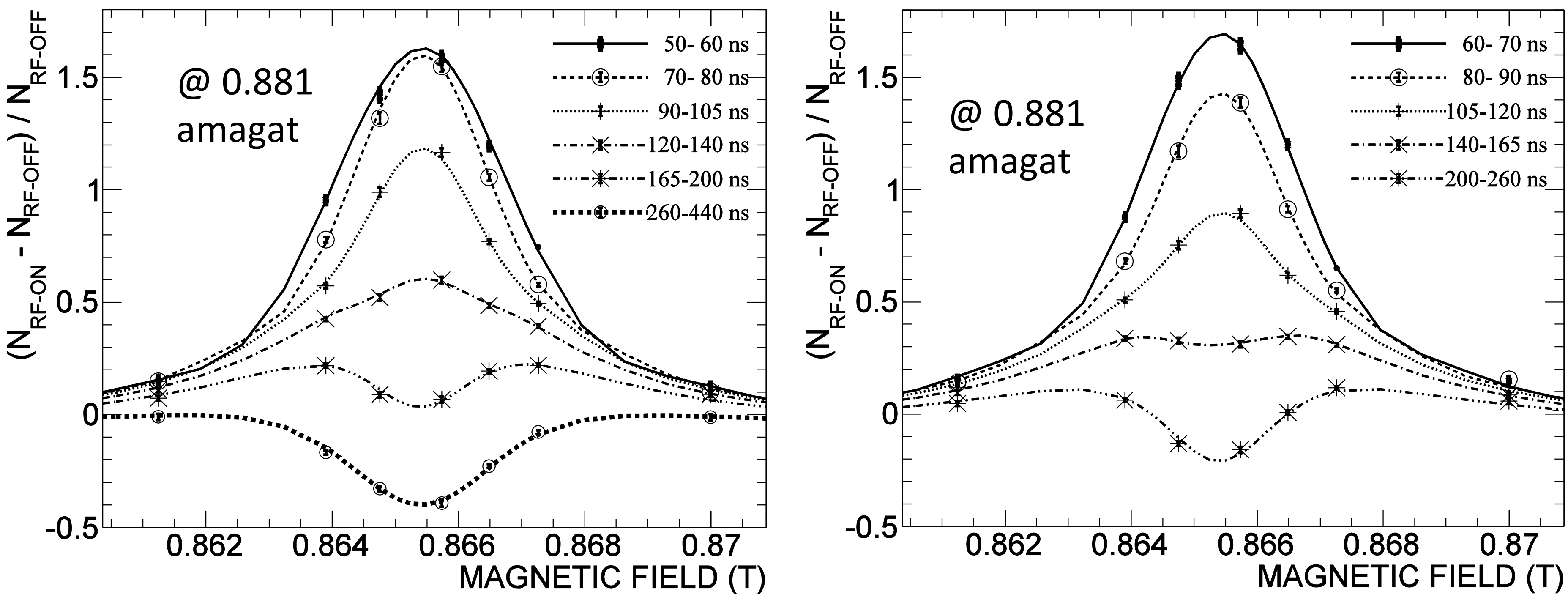


Ps-HFS



$\chi^2/ndf = 633.3 / 592$ ($p = 0.12$)

Fitting result of the resonance lines
Data are well described by theory



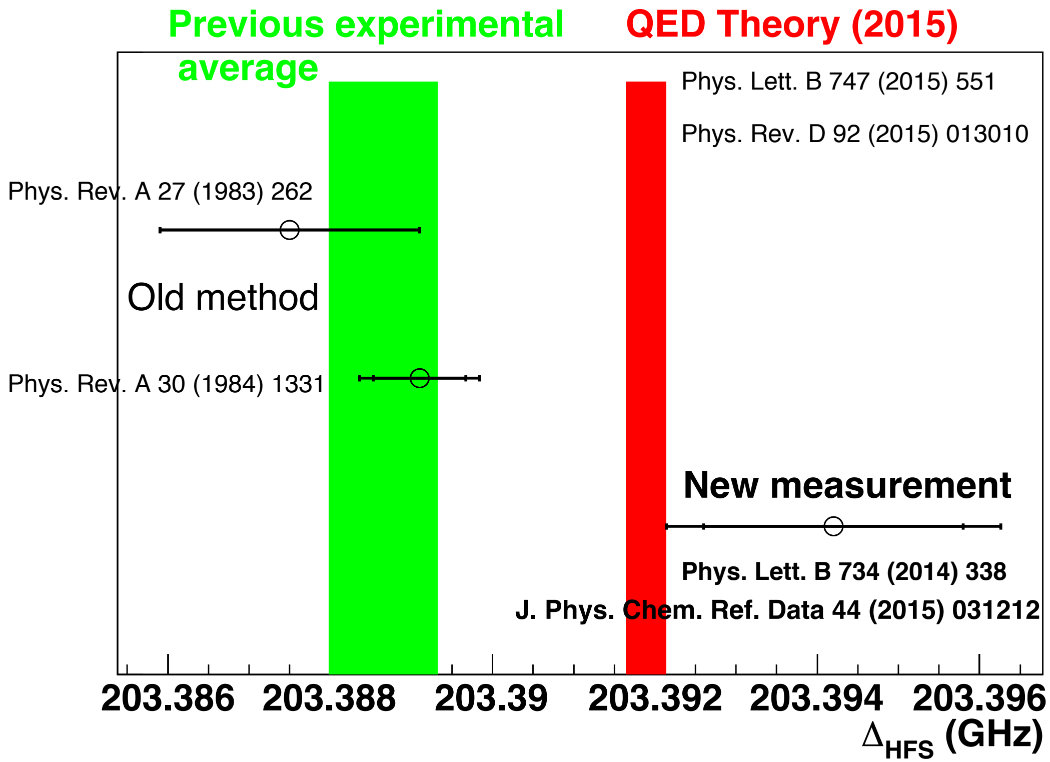
χ^2/ndf = 633.3 / 592 (p = 0.12)

Systematic errors (Main ones)

Category	Source	ppm in Δ_{HFS}
Material Effect	o-Ps pick-off rate	3.5
	Gas density measurement	1.0
	Spatial distribution of density and temperature of gas in the RF cavity	2.5
	Thermalization of Ps	1.9
Magnetic Field	Non-uniformity	3.0
	Offset and reproducibility	1.0
	NMR measurement	1.0
RF	RF power	1.2
	Q_L value of RF cavity	1.2
	RF frequency	1.0
Analysis	Choice of timing window	1.8
	Quadrature sum	6.4

Combined with 8.0 ppm stat. err., Δ_{HFS} = 203.394 2(21) GHz (10 ppm).

Result 1: Center value favored QED



Favors QED calculation

(Consistent with theory within **1.1σ**, disfavors previous experiments by **2.6σ**)

New result taking into account the Ps thermalization was obtained:

Δ_{HFS} = 203.394 2 ± 0.001 6 (stat., 8.0 ppm)

± 0.001 3 (sys., 6.4 ppm) GHz

(total uncertainty = 10 ppm)

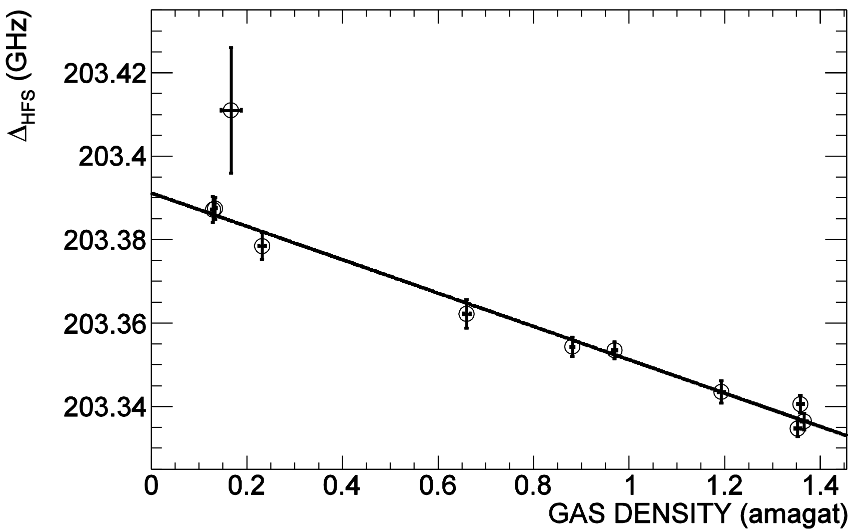
Main systematic errors:

Material effect (o-Ps pickoff, spatial distribution of density and temperature in the RF cavity),

Magnetic field (non-uniformity)

Result 2: Ps thermalization effect = 10 ppm

Fittings of resonance lines WITHOUT
taking into account the time evolutions (Ps thermalization)
= similar method as the previous experiments



→ Gave **10 ± 2 ppm smaller** Ps-HFS value in vacuum

(χ^2/ndf=721.1/592, p=2x10^{-4})

This difference is large enough to explain the 16 ± 4 ppm discrepancy.

Ps thermalization effect is crucial for precision measurement of Ps-HFS.

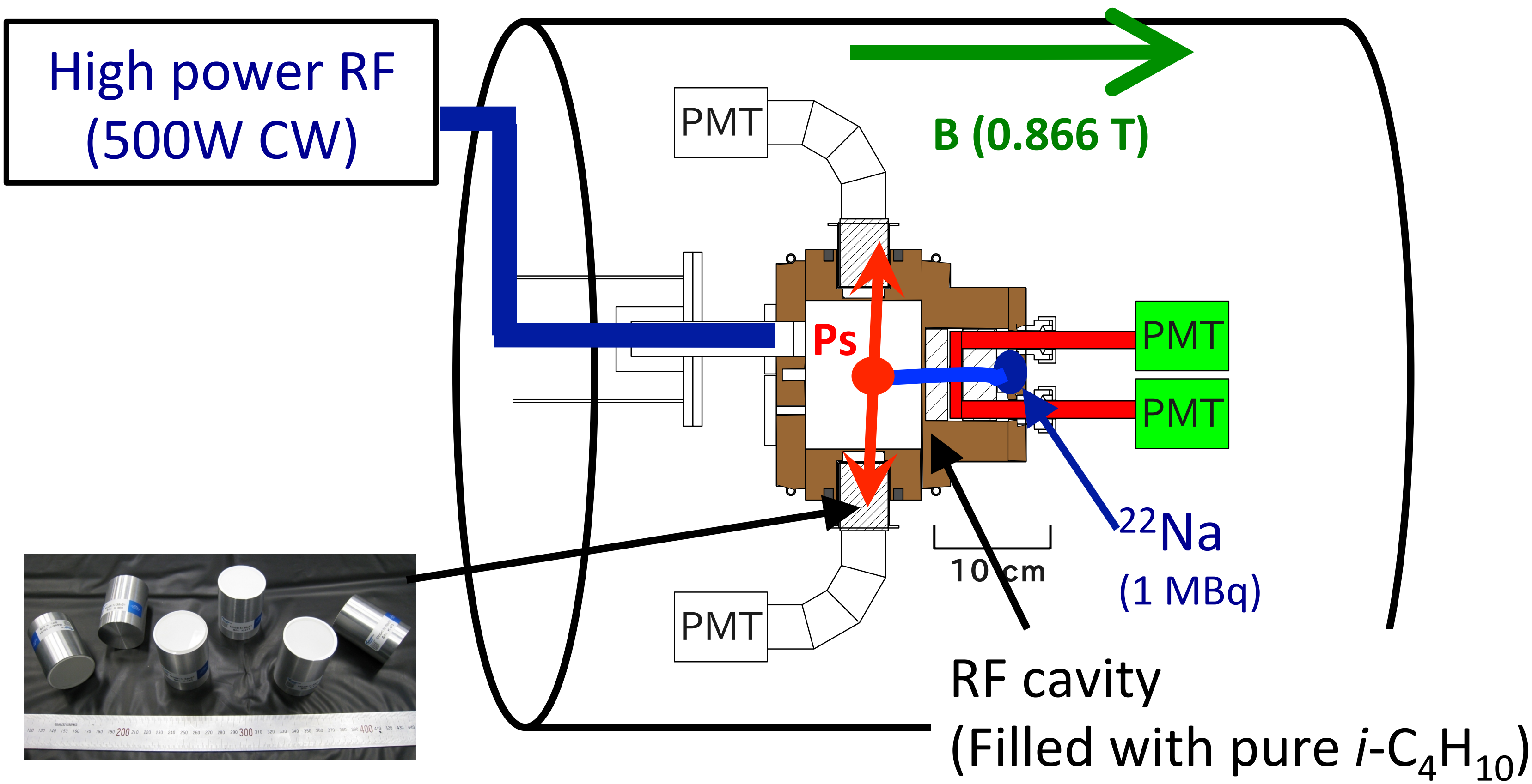
Future prospects

Measurement in vacuum using slow positron beam

(hopefully better than 1 ppm result within 4—5 years)

- High statistics (scan in vacuum instead of extrapolation, higher power RF without discharge)
- Completely free from material effect
- Short measurement period reduces systematic errors

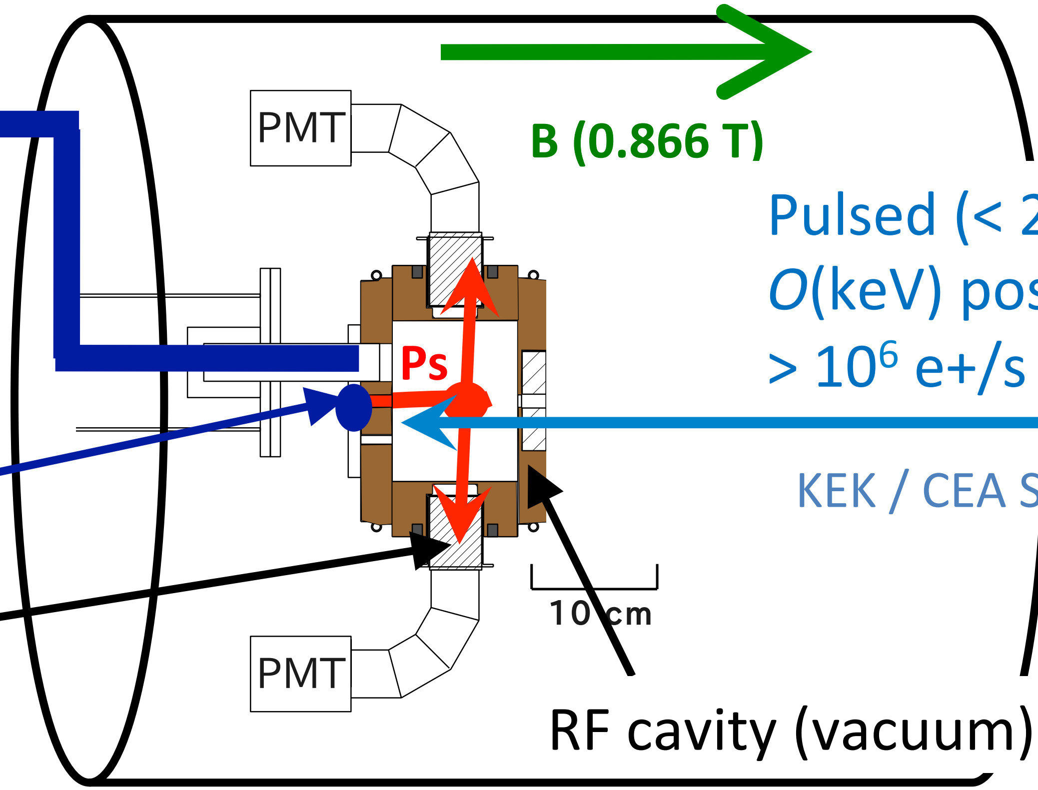
(Current Experimental Setup)



Future Experimental Setup

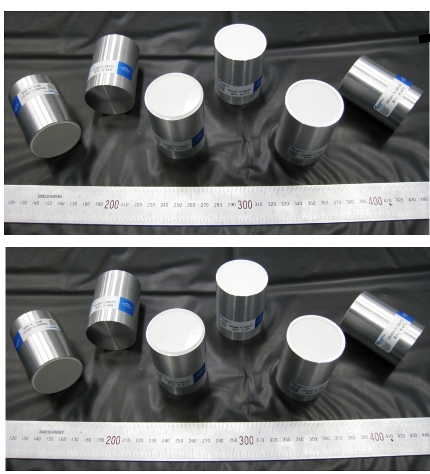
High power RF
(500W CW)

Ps formation in vacuum (> 40%)
(Hot metal or Porous Silica)



Pulsed (< 2ns, > 50 Hz)
O(keV) positron beam
> 10^6 e+/s

KEK / CEA Saclay / Tokyo

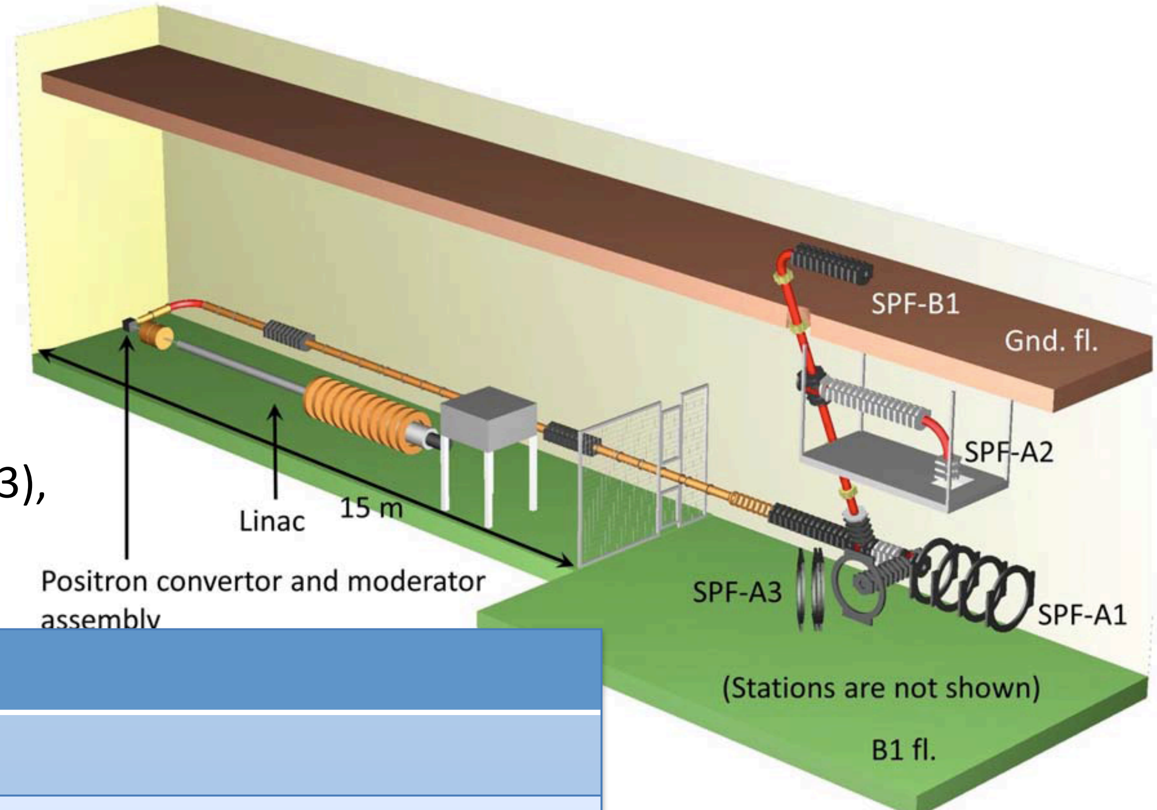


γ-ray detectors x 12
Digitization of waveforms of detector signals
(~100% separation for Δt > 8 ns (*preliminary*))

→ 1 ppm result by a few-week run

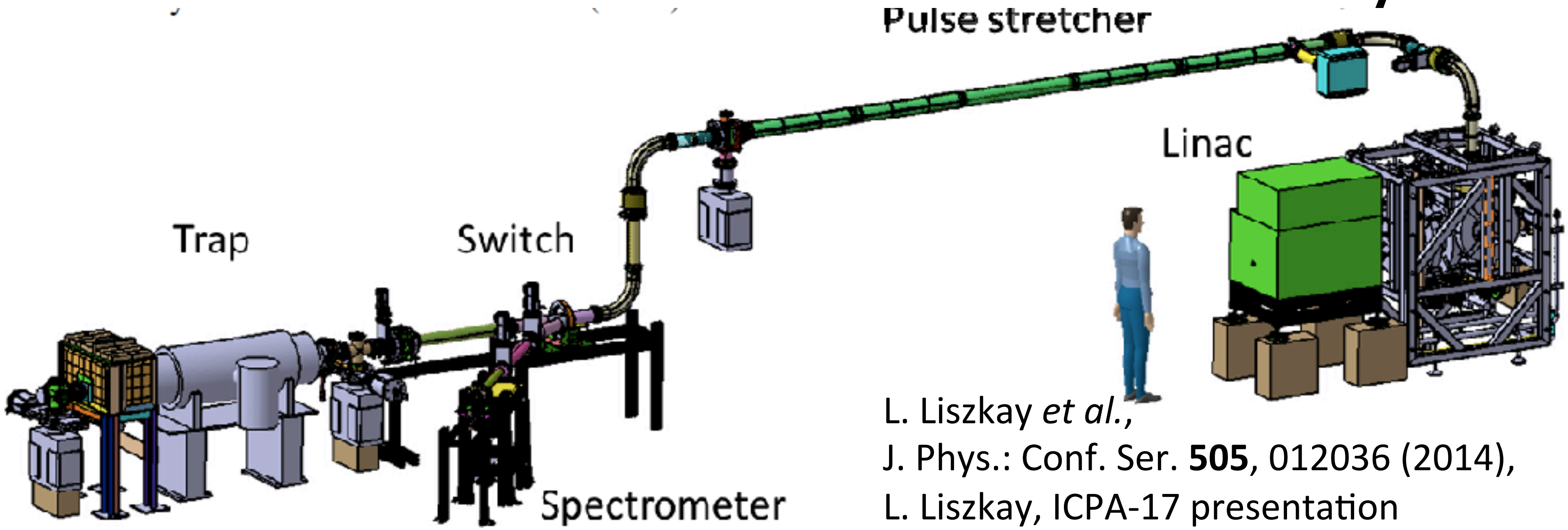
Beam line candidate 1: KEK

K. Wada *et al.*,
J. Phys.: Conf. Ser. **443**, 012082 (2013),
T. Hyodo, ICPA-17 presentation



Property	KEK
Beam intensity	**5e+6 e+/s**
Pulse length	**1—10 ns**
Pulse repetition rate	50 Hz
Possible beam time	Strictly less than 1 week
Magnet space	Tight? Effect on other beamlines?
Magnet transport	**Easy (inside KEK)**
Support	Helium, magnet

Beam line candidate 2: CEA Saclay



L. Liszkay *et al.*,
J. Phys.: Conf. Ser. **505**, 012036 (2014),
L. Liszkay, ICPA-17 presentation

Property	CEA Saclay
Beam intensity	3e+6 e+/s
Pulse length	2.5 us (need to develop buncher)
Pulse repetition rate	**200 Hz**
Possible beam time	**More than a half year?**
Magnet space	A bit tight, need support for 13t magnet.
Magnet transport	Difficult, expensive, long
Support	Helium, manpower, etc.

Other new approaches

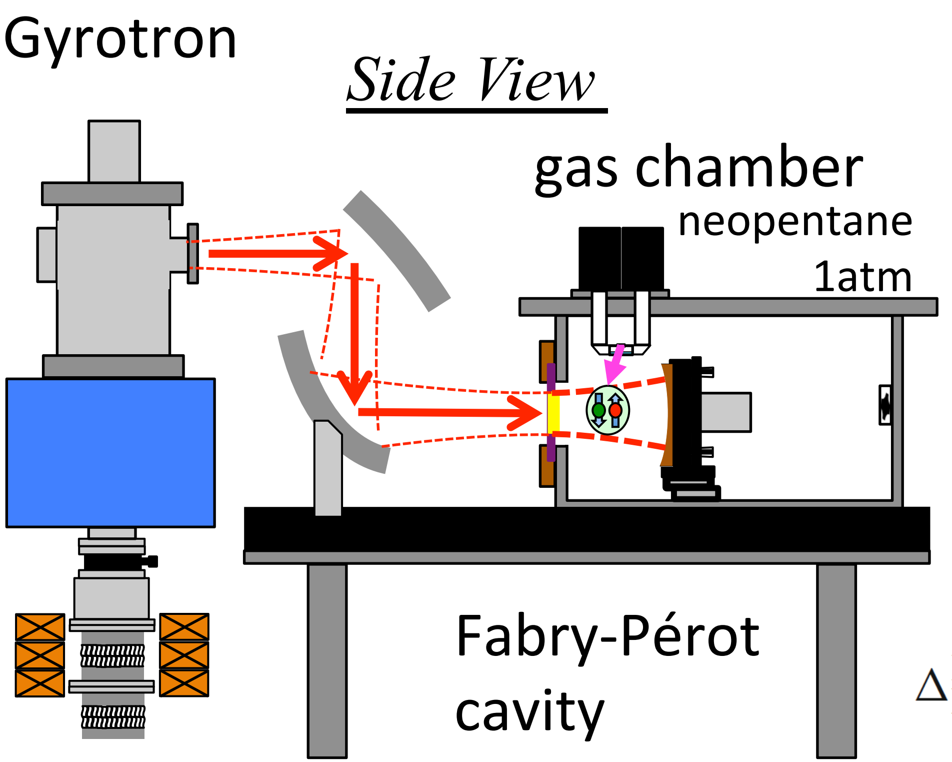
New Experiment 1 (Tokyo)

- First millimeter-wave spectroscopy

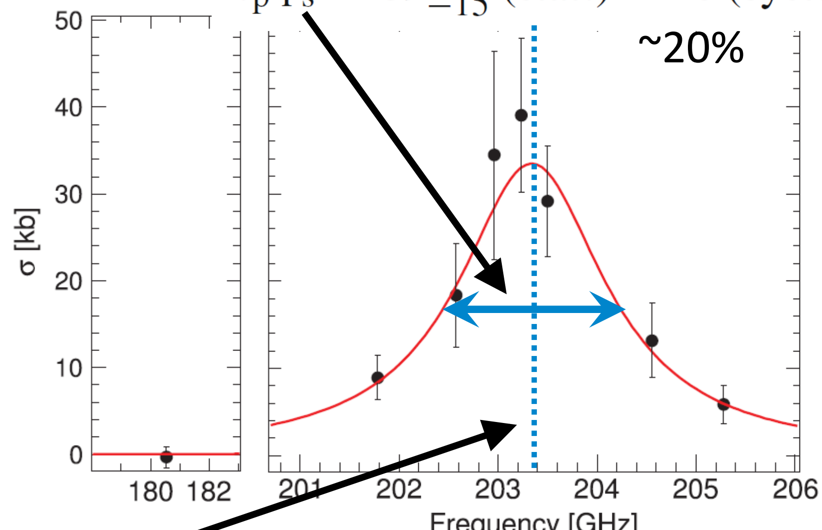
  (A. Miyazaki *et al.*, PTEP **2015**, 011C01 (2015))

  First direct measurement of HFS transition

  using a frequency-tunable Gyrotron.



$$\tau_{\text{p-Ps}} = 89^{+18}_{-15}\,(\text{stat.}) \pm 10\,(\text{syst.})\ \text{ps}$$

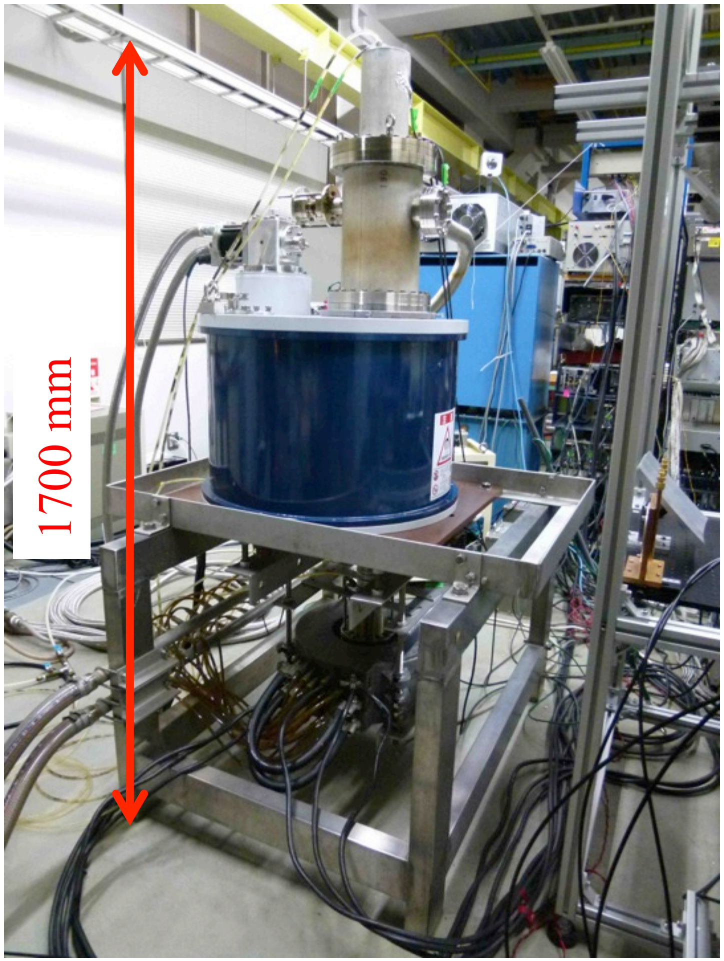


$$\Delta^{\text{HFS}}_{\text{Ps}} = 203.39^{+0.15}_{-0.14}\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{GHz}$$

~ 900 ppm

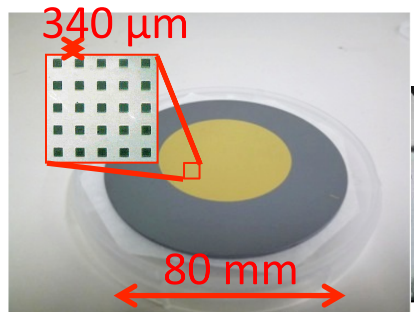
New Experiment 1 (Tokyo)

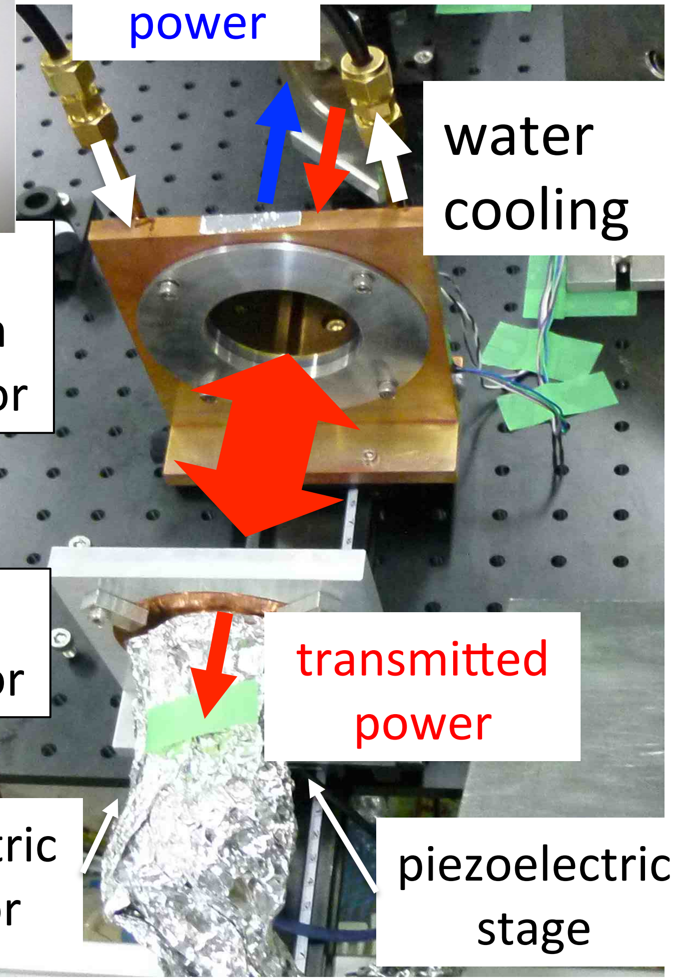
Developed gyrotron collaboration with Fukui University (Japan)



Y. Tatematsu, et al., J. Infrared Milli. Terahz Waves 33, 292 (2012)

Fabry-Pérot cavity



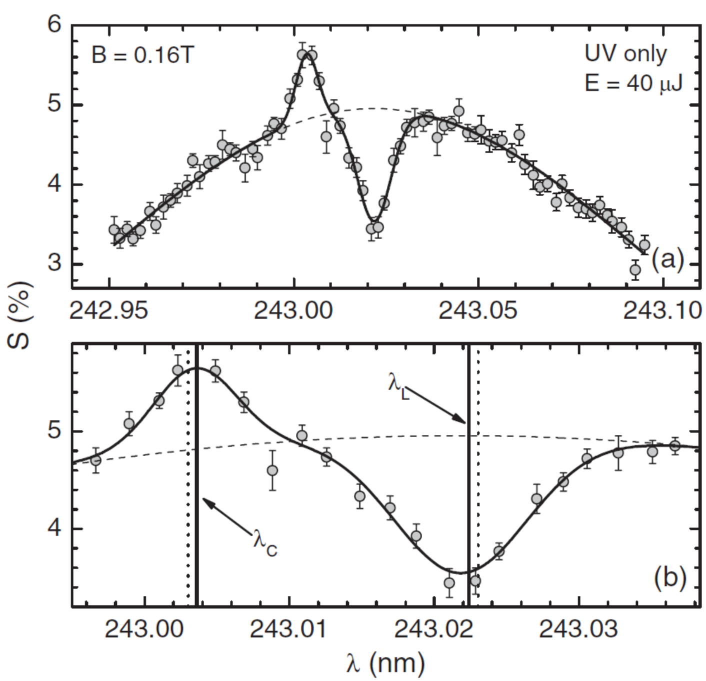


New Experiment 2 (UC Riverside)

- Saturated Absorption Spectroscopy (SAS)

  (D. B. Cassidy *et al.*, PRL **109**, 073401 (2012))

  Measure the 1*S*-2*P* (Lyman-α) transition (243 nm) of Ps.
  Ps-HFS can be measured by a crossover resonance due to Zeeman mixing of singlet and triplet states in the 2*P* manifold.



$$\nu_{\rm hfs} = 2(\nu_C - \nu_L) + \underline{(\nu_C + \nu_L)R},$$

Recoil shift

$$E_{\rm hfs} = 198.4 \pm 4.2 \text{ GHz}$$

~ 2%

Conclusion

- *Ps-HFS puzzle:* a large 4.5 σ discrepancy of Ps-HFS between the previous experimental values and theoretical calculation.
- New precise microwave spectroscopy using the Zeeman effect was recently performed.
  - Used new techniques to reduce possible systematic uncertainties in the previous experiments (Non-thermalized Ps effect and Non-uniformity of magnetic field).
  - Δ_{HFS} = 203.3942(21) GHz (10 ppm)   Favors QED calculation
  - Ps thermalization effect was found to be as large as 10 ± 2 ppm.
- Other approaches are also in progress and the techniques are interesting.
- Future measurements will be performed in vacuum using slow positron beam (hopefully a new result within 4—5 years).