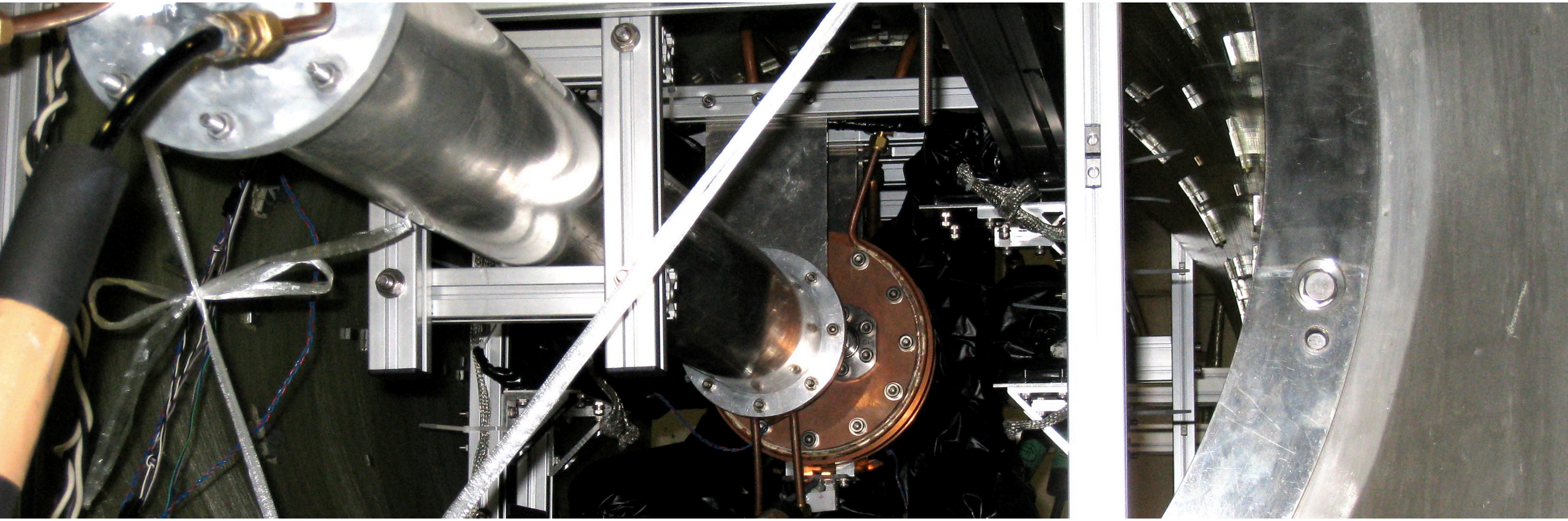
New measurements of the Positronium Hyperfine Splitting



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Outline

- Introduction: Positronium Hyperfine Splitting (Ps-HFS) *puzzle*
- Material effect and Ps thermalization
- New Experiment
  - ➢ Precise microwave spectroscopy using the Zeeman effect (A. Ishida *et al.,* Tokyo, 2014)
- Other New Methods
  - ➢ First millimeter-wave spectroscopy

    (A. Miyazaki *et al.*, Tokyo, 2015)
  - ➢ Saturated Absorption Spectroscopy (SAS)

    (D. B. Cassidy *et al.*, UC Riverside, 2012)
- Prospects & conclusion

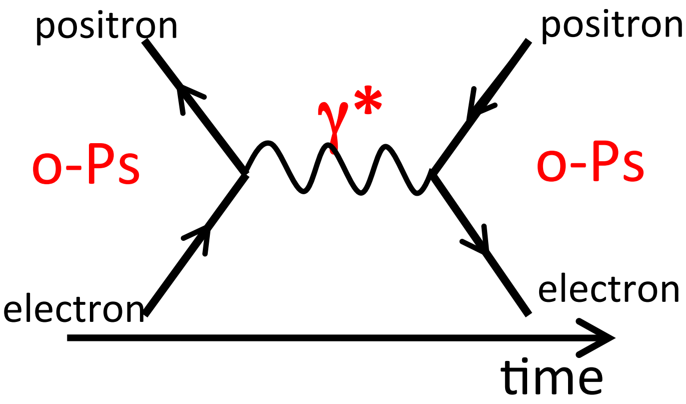
Positronium Hyperfine Splitting (Ps-HFS) and its characteristics

Energy difference between two spin eigenstates of the ground state Ps

→ Ps-HFS (203 GHz)

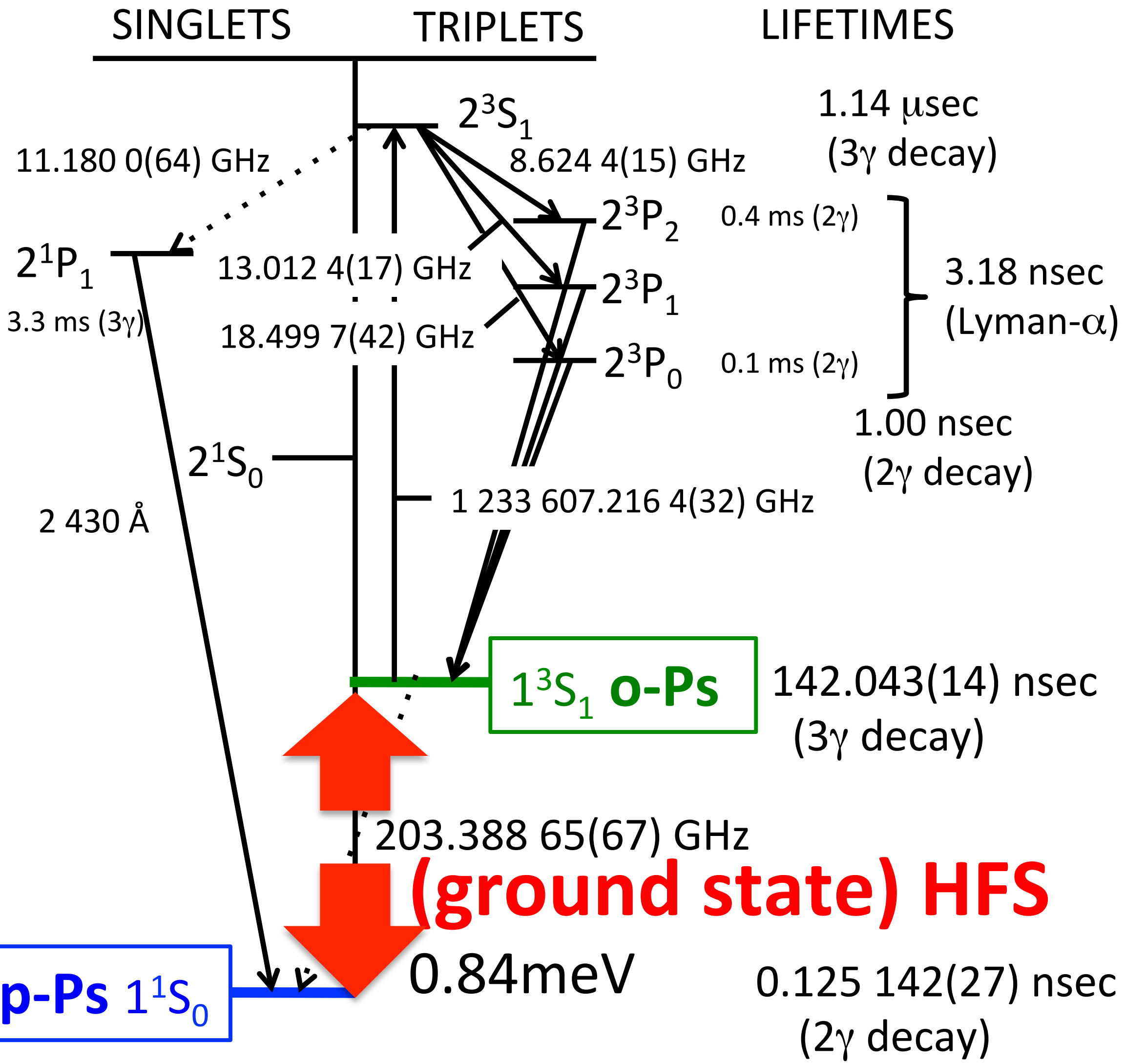
$$\mu = \frac{e}{2m}\sigma$$

spin-spin interaction



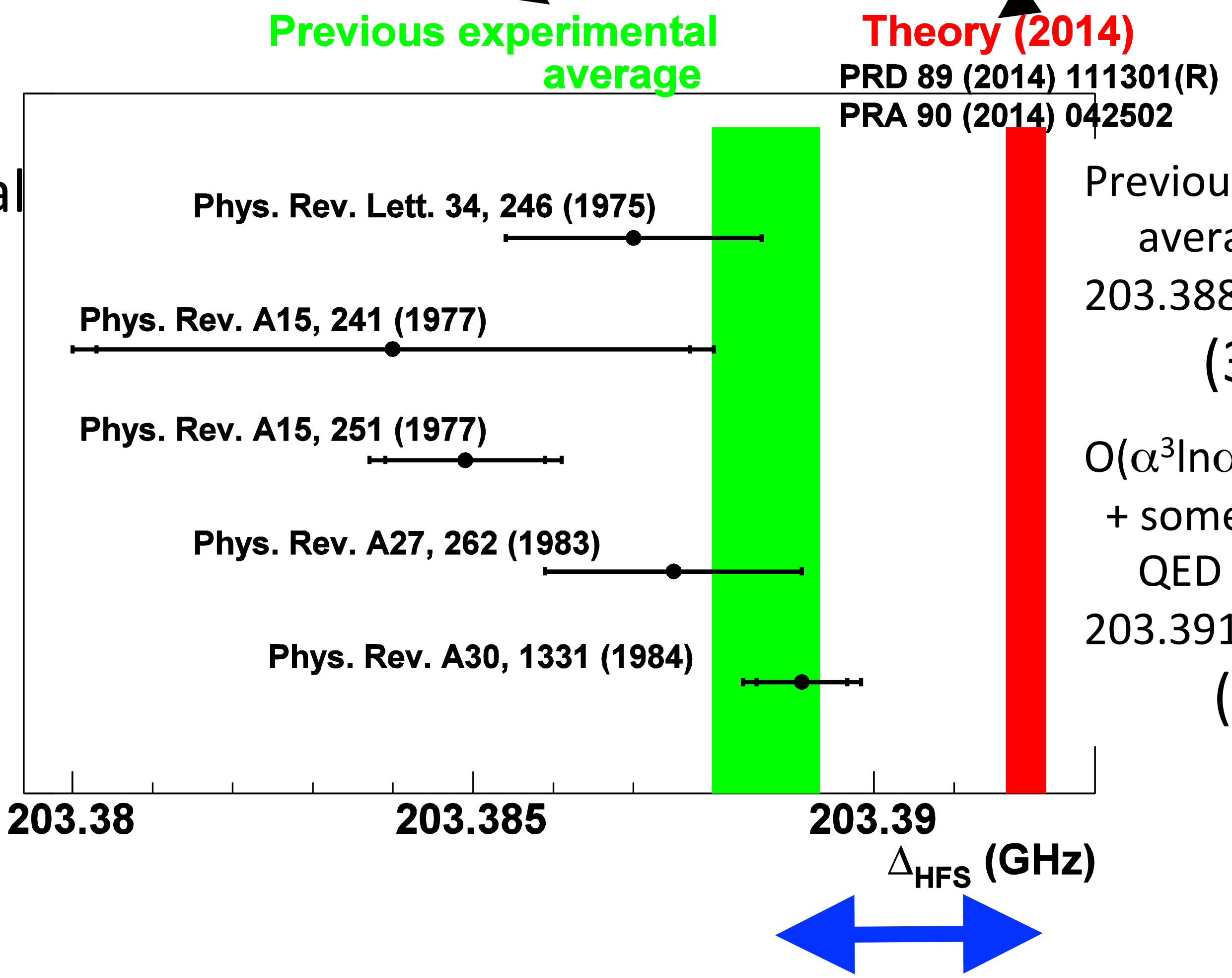
Quantum oscillation effect is also large (40%)

→ Sensitive to new physics beyond SM



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)

$O(\alpha^3 \ln\alpha^{-1})$
+ some of $O(\alpha^3)$
QED theory
203.391 90(25) GHz
(1.2 ppm)

16 ppm (4.5 σ) significant discrepancy

Use 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 are 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.

Estimation of Material Effect in previous experiments

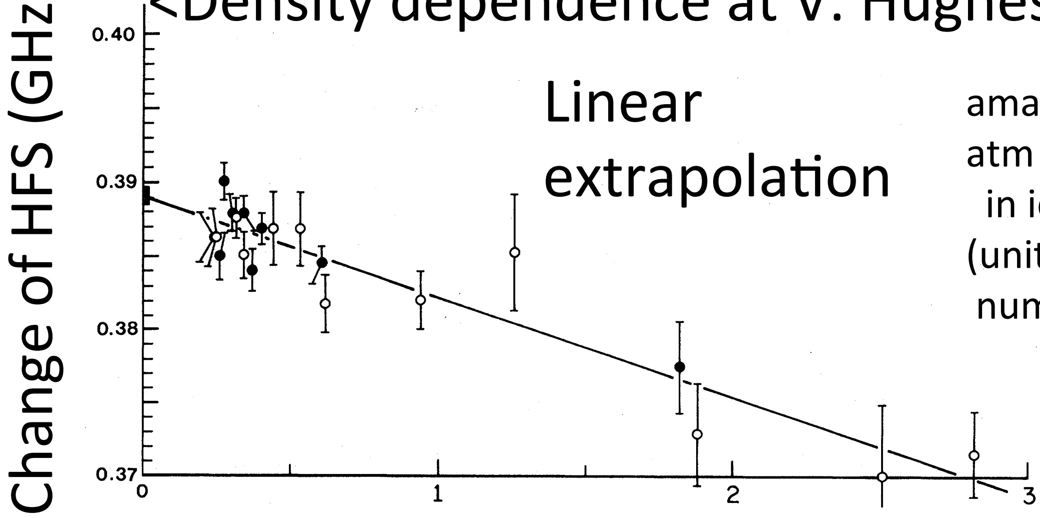
- Need material (gas molecules) so that positron can be cooled down, and form Ps → Ps feels electric field of molecules

Strength of the Stark Effect
(∝ ~ Collision rate with surrounding molecules)
$\propto$ (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.*>



Linear extrapolation

amagat = atm @ 0 °C in ideal gas (unit of number density)

N$_2$ gas density (amagat)

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).

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

Ps thermalization and its effect on Ps-HFS

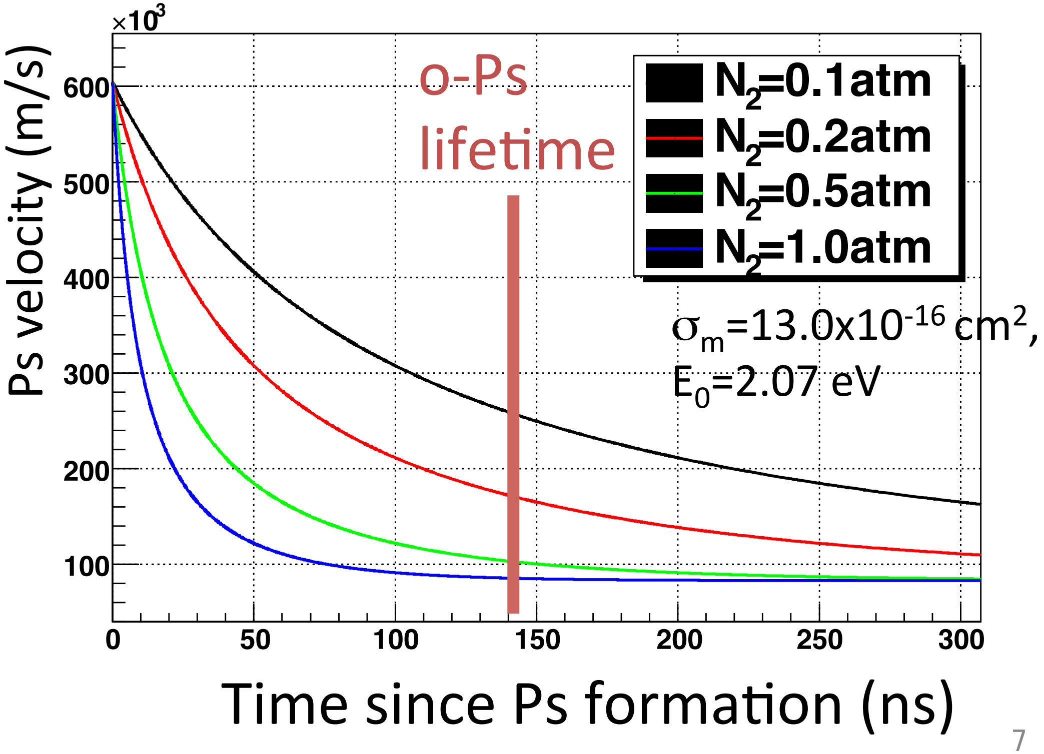
Strength of the Stark Effect
(∝ ~ Collision rate with surrounding molecules)
∝ (Density of molecules) x (Ps velocity $v(t))^{3/5}$

Ps loses its kinetic energy and gets room temperature
= Thermalization

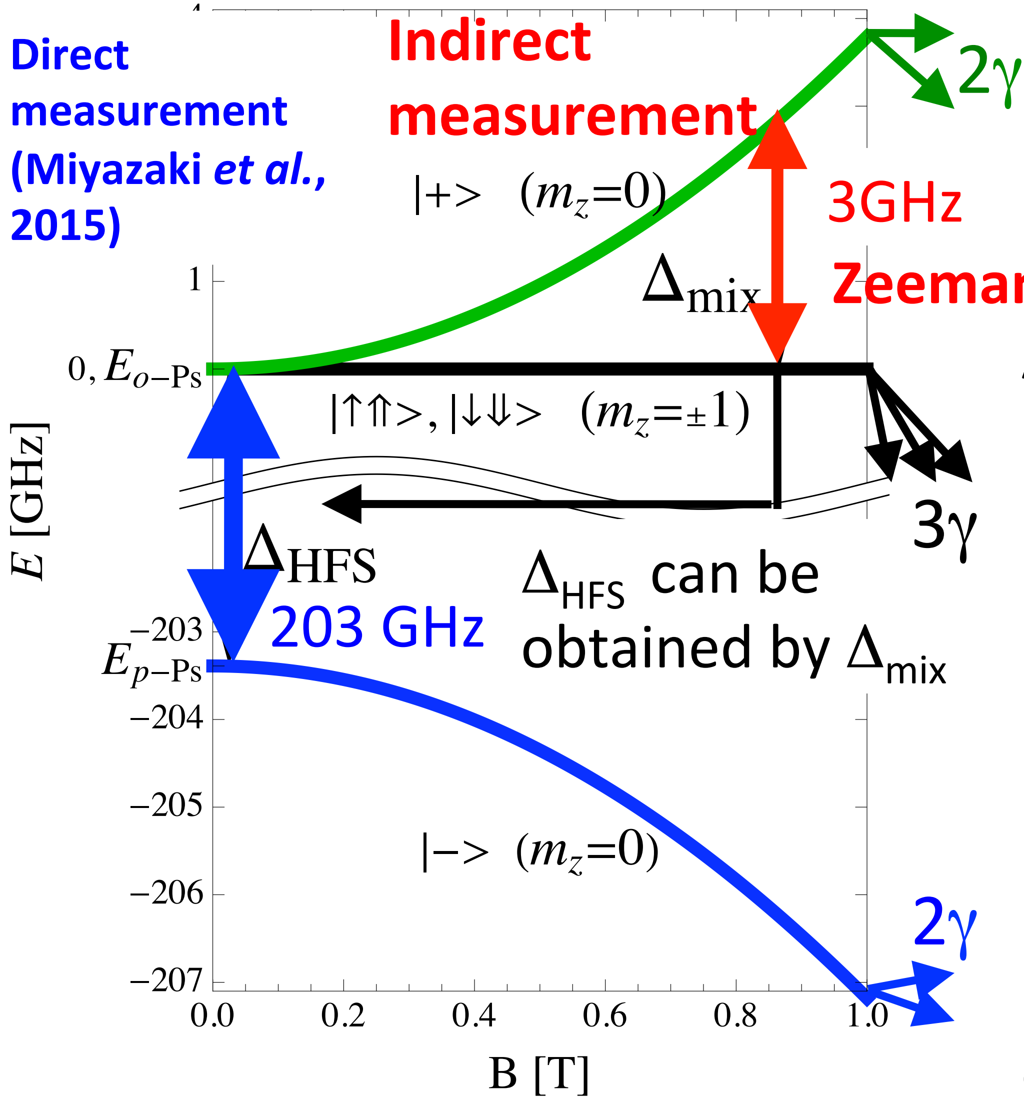
It takes longer time to thermalize in lower density
→ Linear extrapolation could be a large systematic uncertainty

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

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



Experimental technique: Indirect Measurement using Zeeman Effect



Zeeman transition

Δ_{HFS} can be obtained by Δ_{mix}

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.

New Experimental Setup

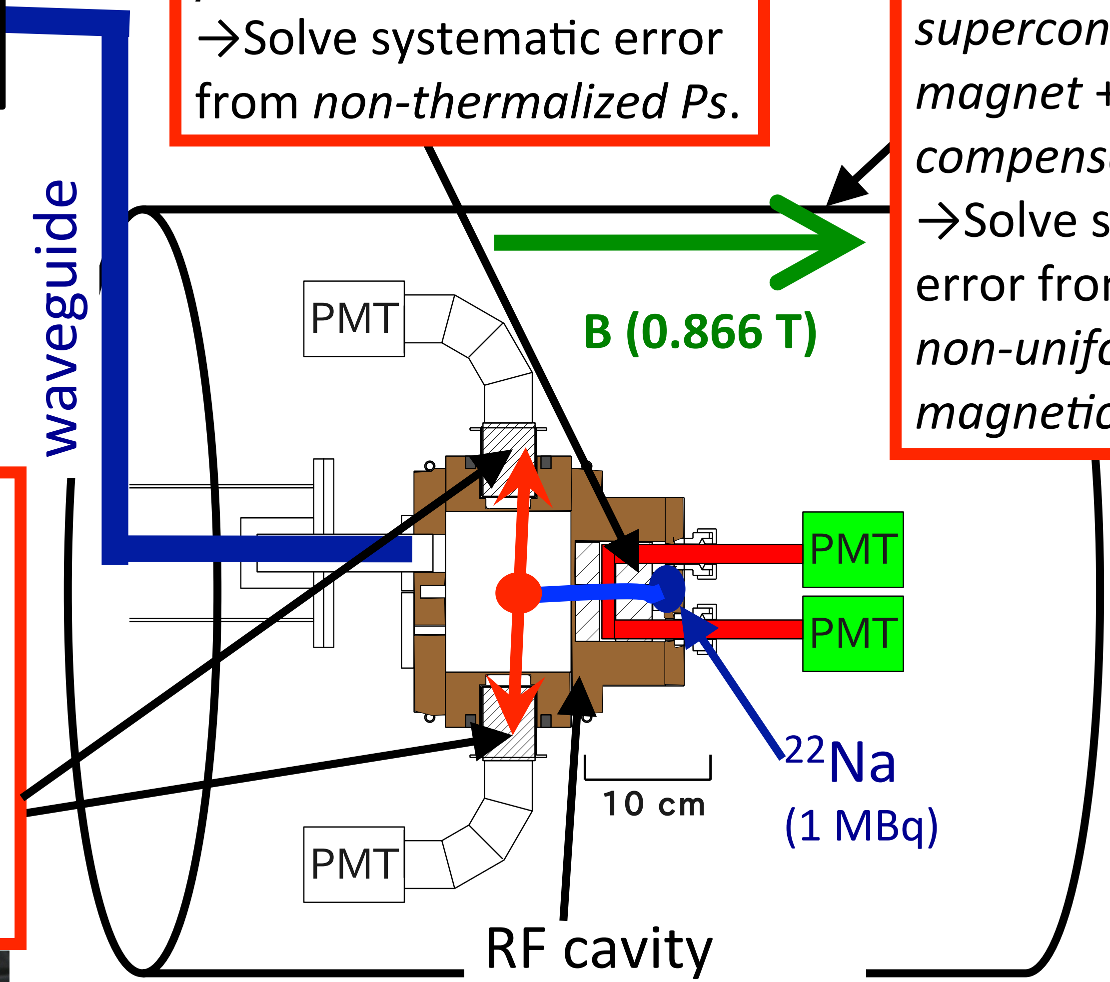
High power RF
(500W CW)

2

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

1

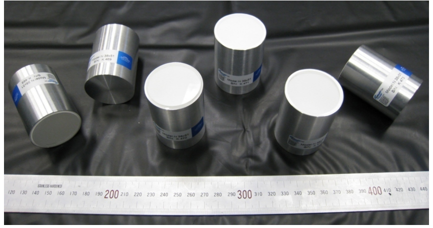
Large bore superconducting magnet + compensation coils
→Solve systematic error from *non-uniformity of magnetic field.*



2

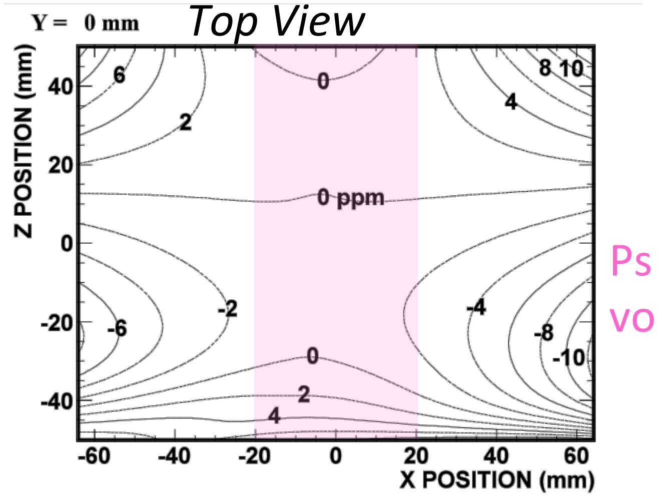
High performance γ-ray detectors
($LaBr_3$ scintillators)

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

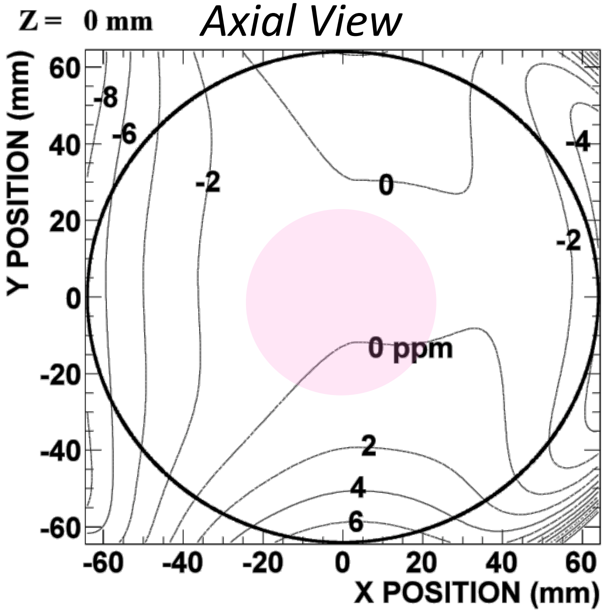


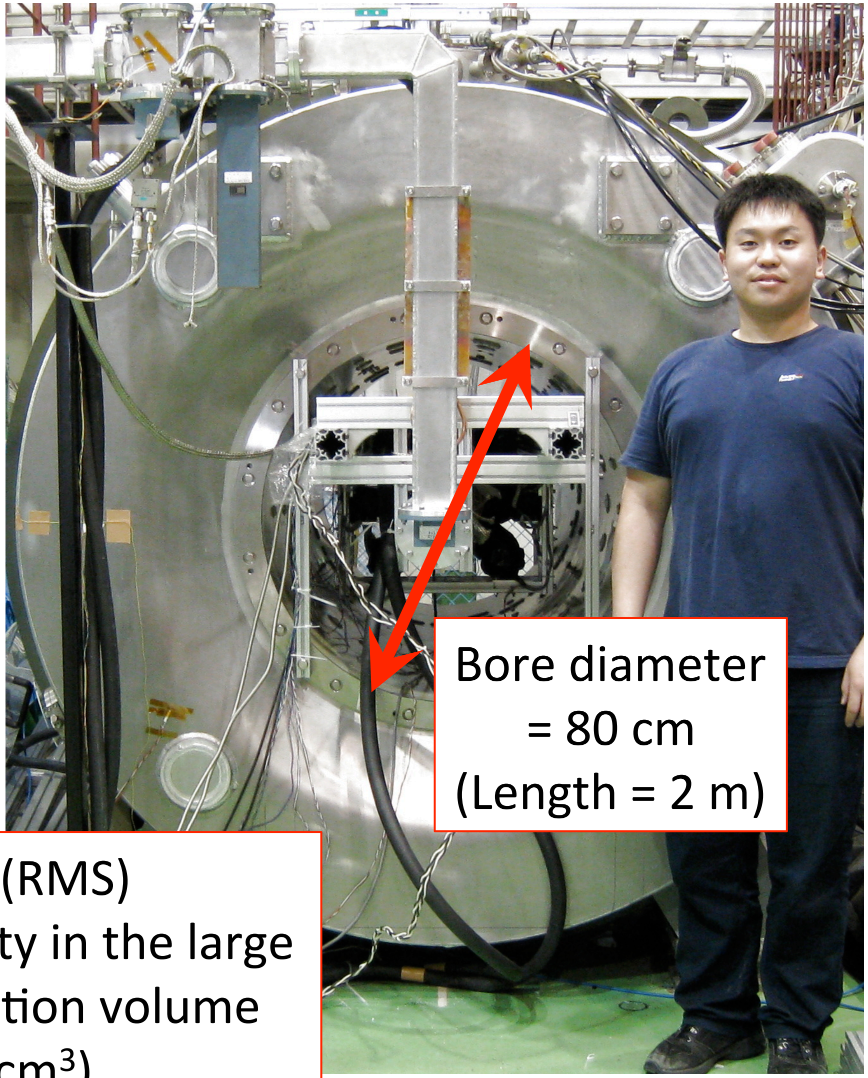
RF cavity
(Filled with pure i-C_4H_{10})

New technique 1:
Large-bore superconducting magnet



Ps formation volume

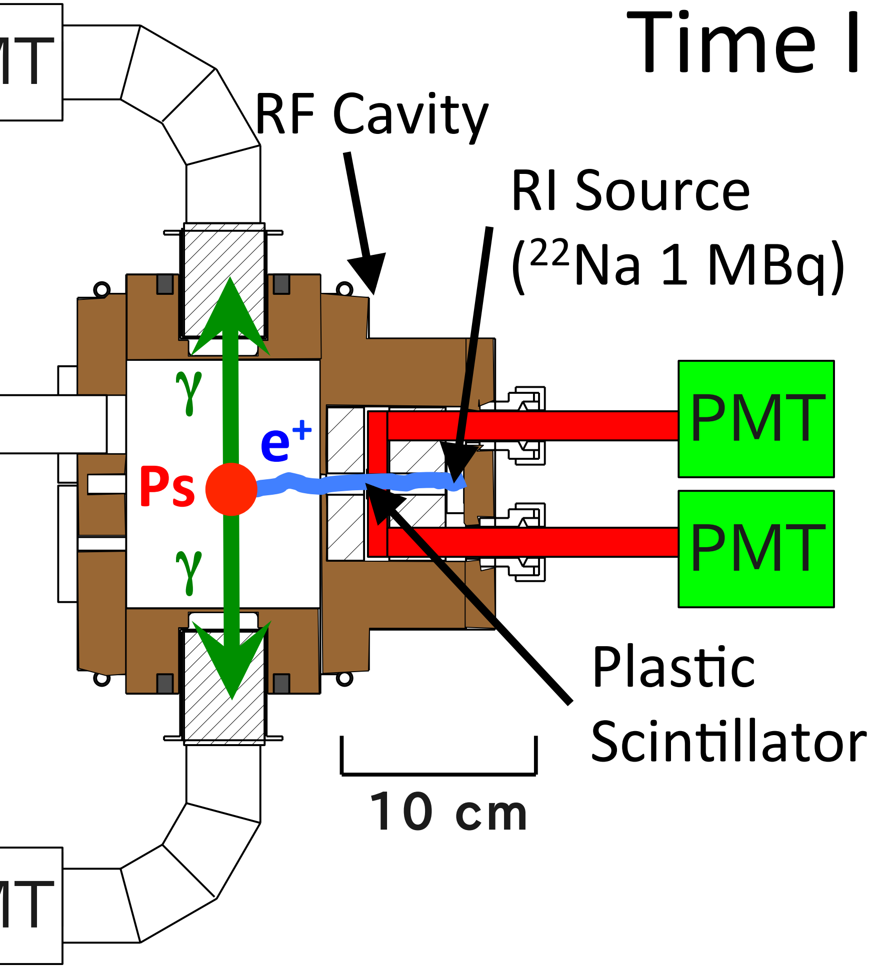




Bore diameter
= 80 cm
(Length = 2 m)

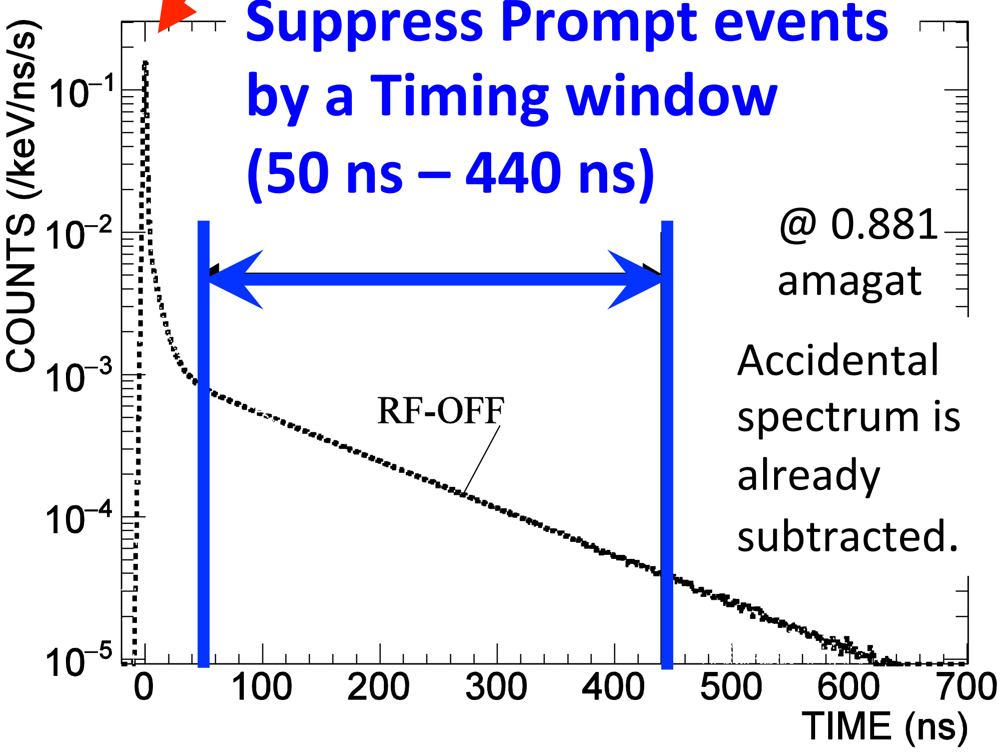
1.5 ppm (RMS) uniformity in the large Ps formation volume (~ 100 cm^3).

New technique 2:
Time Information



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

→ *t=0*



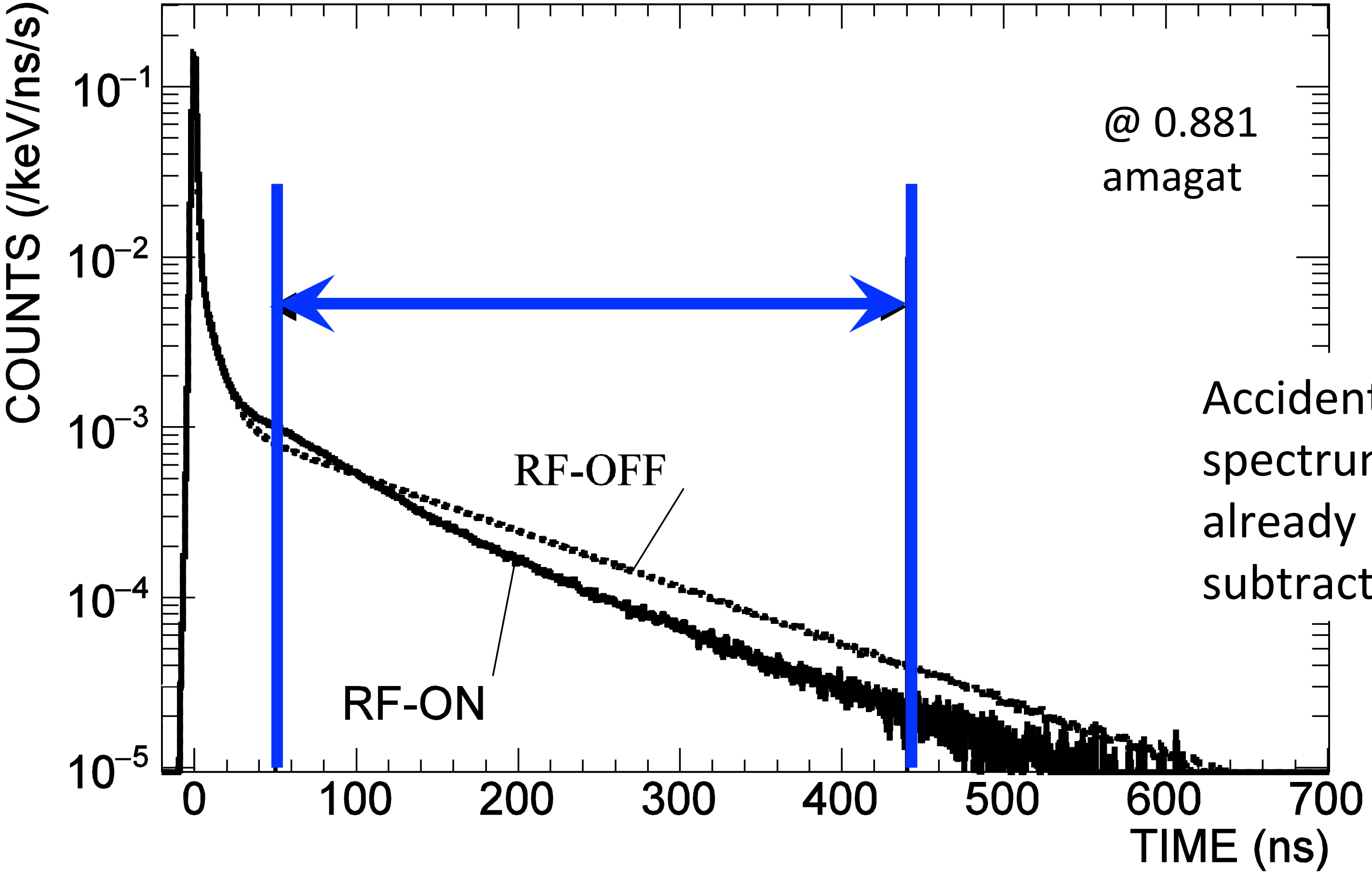
Suppress Prompt events by a Timing window (50 ns – 440 ns)

@ 0.881 amagat

Accidental spectrum is already subtracted.

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

Comparison of timing spectra (RF-ON/OFF)



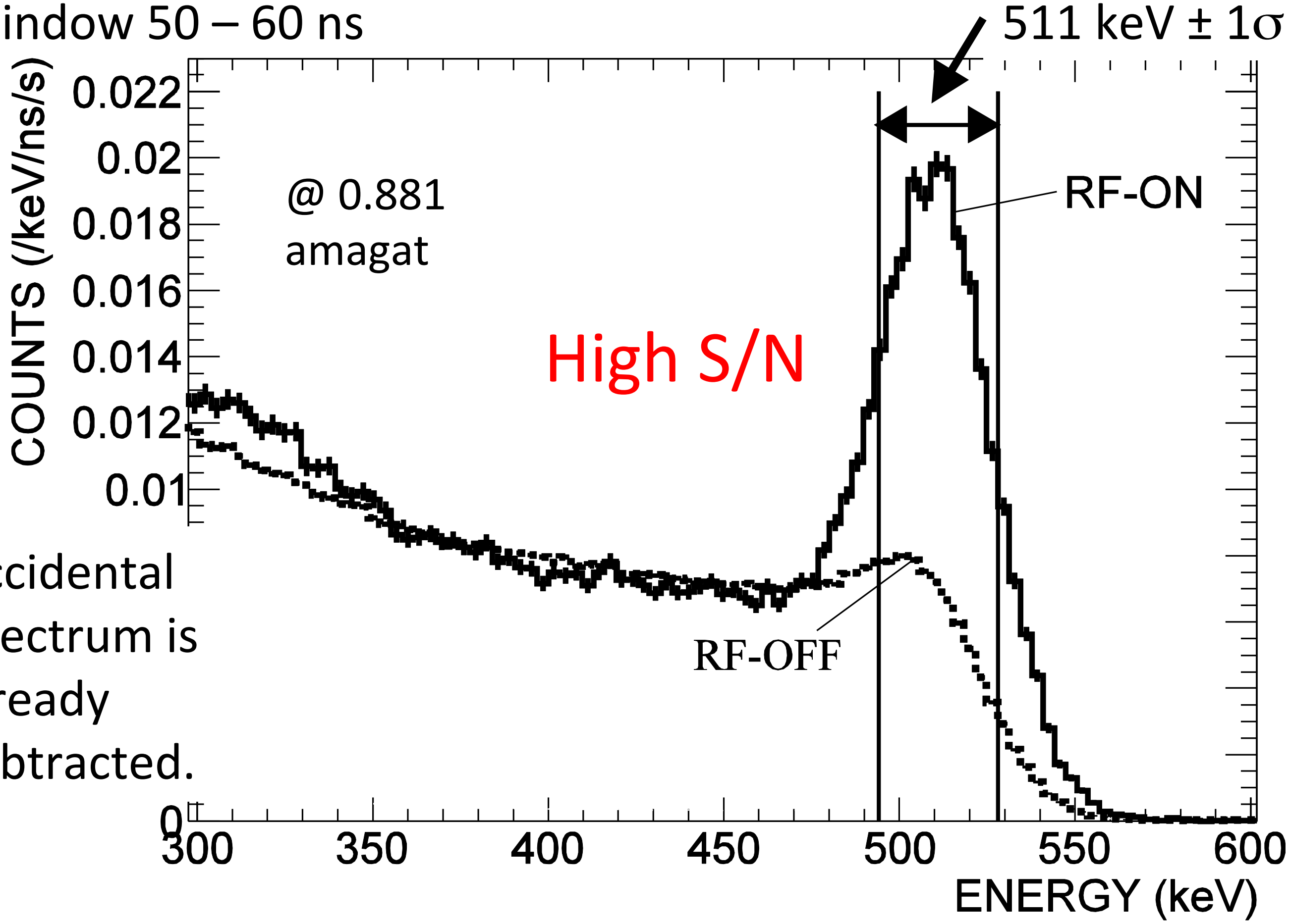
@ 0.881 amagat

Accidental spectrum is already subtracted.

Lifetime is clearly shortened by RF due to the Zeeman transition.

Comparison of energy spectra (RF-ON/OFF)

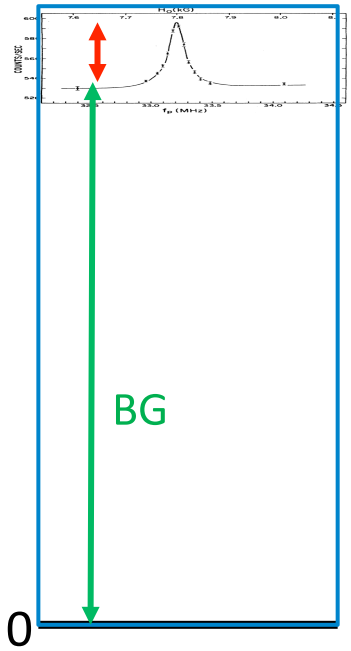
timing window 50 – 60 ns



High S/N

Accidental spectrum is already subtracted.

cf. S/N of previous experiment

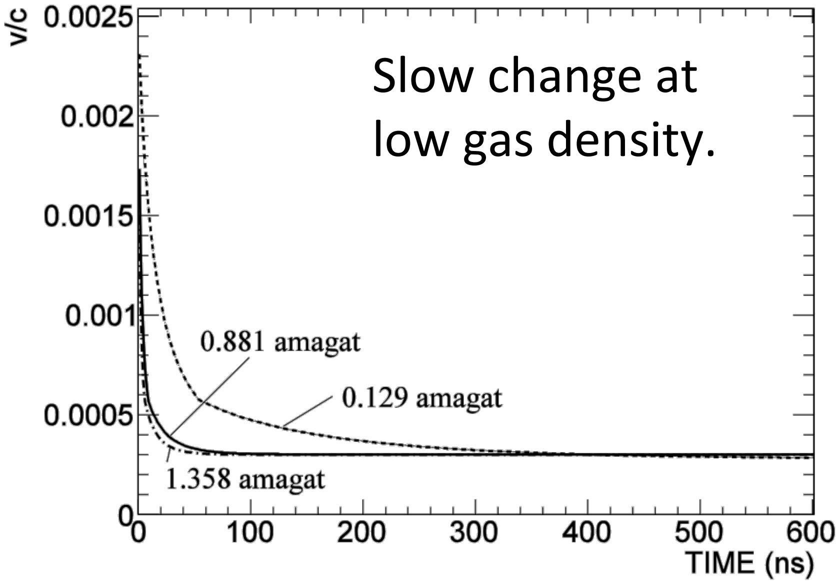


2γ decay rate increases because of the Zeeman transition. Use (RF-ON − RF-OFF) / RF-OFF of count rates in the 511 keV ± 1σ energy window.

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

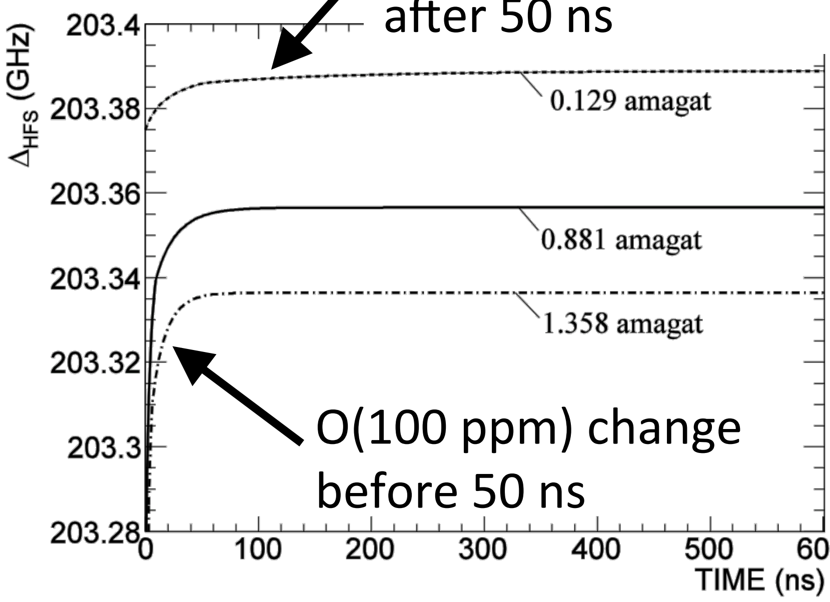
- Scanned by Magnetic Field with the fixed RF frequency and power.
- 50—440 ns is divided to 11 sub timing windows.
- Simultaneous fit of all of the gas density, magnetic field strength, and (sub) timing windows.
- Time evolution of Ps velocity (thermalization) and Δ_{HFS} ($\propto nv^{3/5}$) is taken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

Ps velocity / c



Slow change at low gas density.

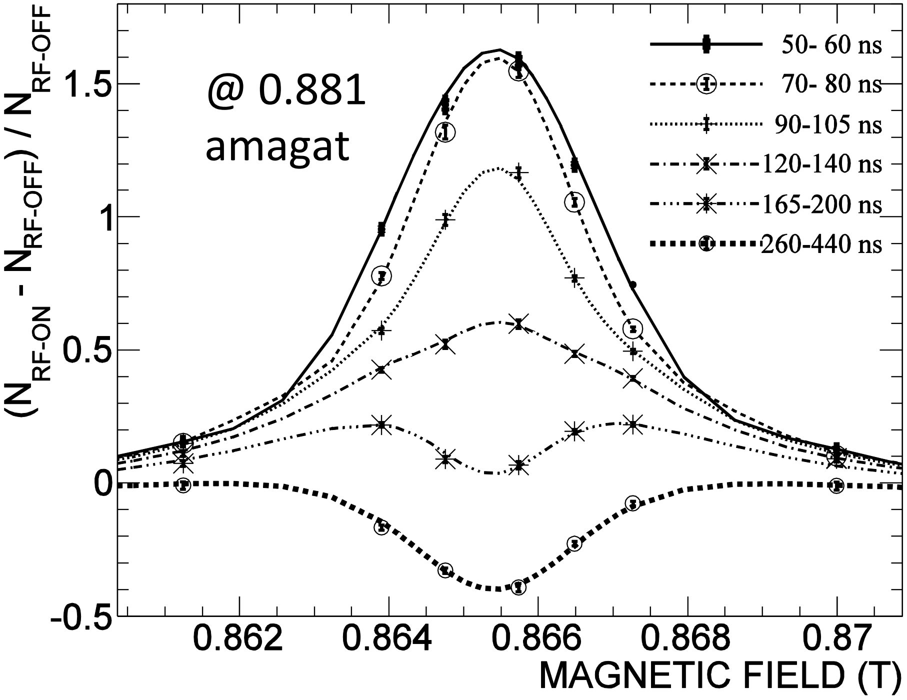
Ps-HFS

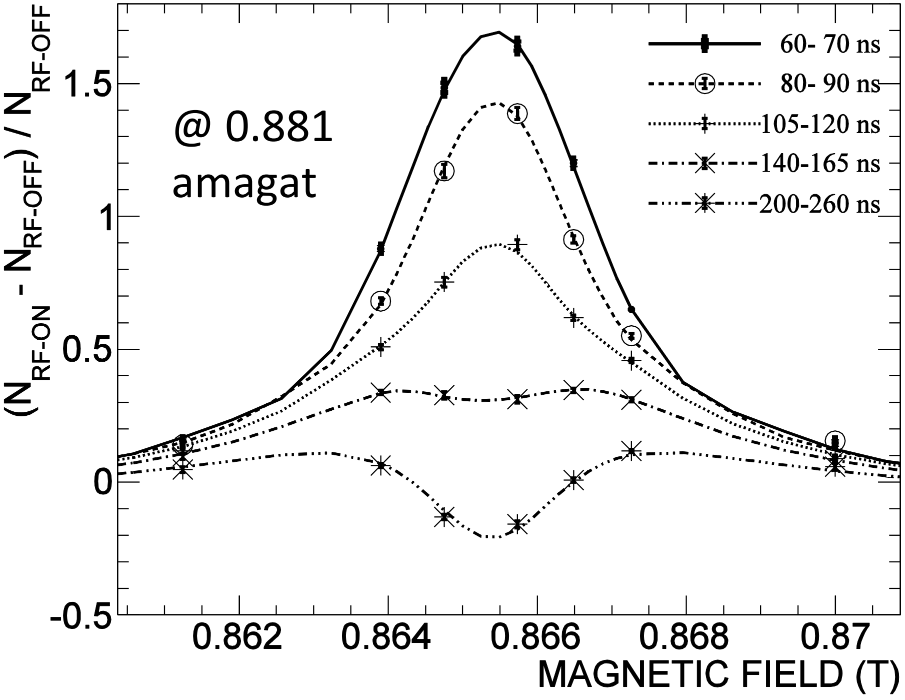


O(10 ppm) change after 50 ns

O(100 ppm) change before 50 ns

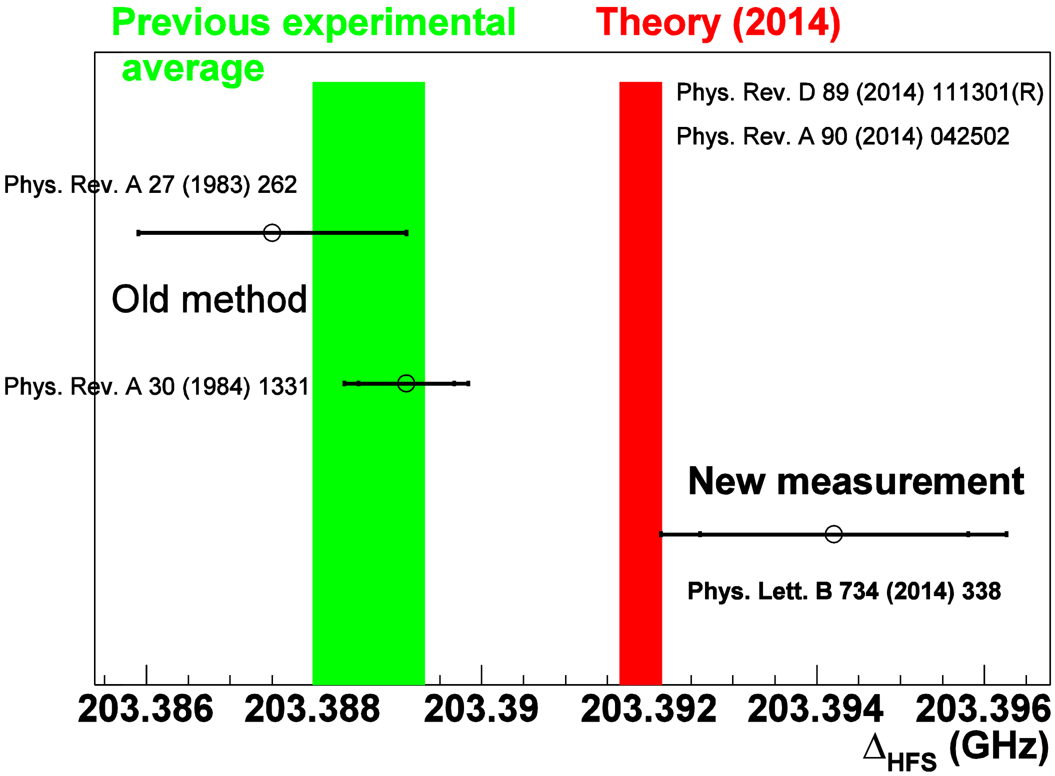
Fitting result of the resonance lines
Data are well described by theory





χ^2/ndf = 633.3 / 592 (p = 0.12)

Result 1: Center value favors QED



Favors QED calculation

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

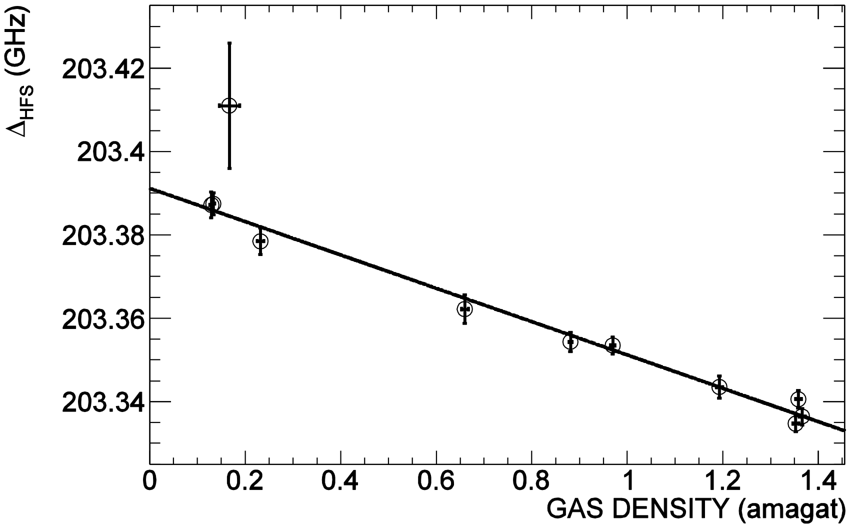
New result taking into account the Ps thermalization is:

$$\Delta_{HFS} = 203.394\,2 \pm 0.001\,6 \text{ (stat., 8.0 ppm)}$$
$$\pm 0.001\,3 \text{ (sys., 6.4 ppm) GHz}$$
$$\text{(total uncertainty = 10 ppm)}$$

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



→ Gives **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.

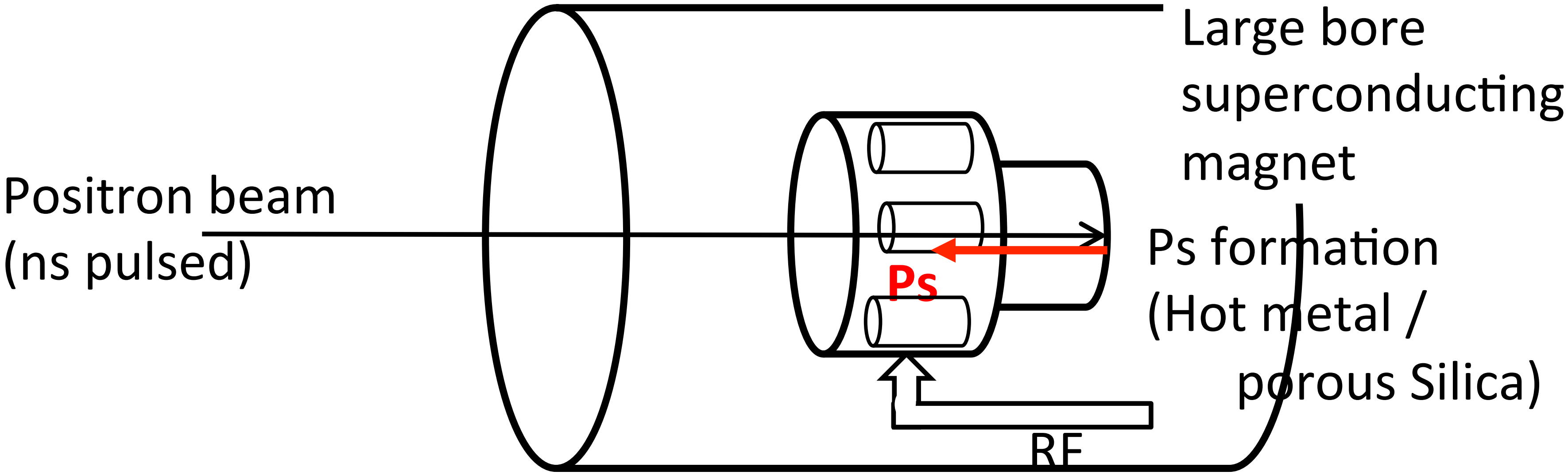
Ps thermalization effect is crucial for precision measurement of Ps-HFS.

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



Large bore superconducting magnet

Positron beam (ns pulsed)

Ps

Ps formation (Hot metal / porous Silica)

RF

Future prospects

Estimations:

1. Pulsed positron beam
    - beam energy: O(keV)
    - beam intensity: > 10^6 e+/s
    - Pulse width: < 2 ns
    - Repetition rate: > 50 Hz
2. Ps formation
    - > 40% formation fraction of 1*S* Ps
3. Detectors, RF, DAQ system
    - 12 x $LaBr_3(Ce)$ γ-ray detectors
    - 500 W CW Microwave with higher Q_L value cavity
    - Digitization of waveforms detector signals

→ 1 ppm result by a few-week run

Other new approaches

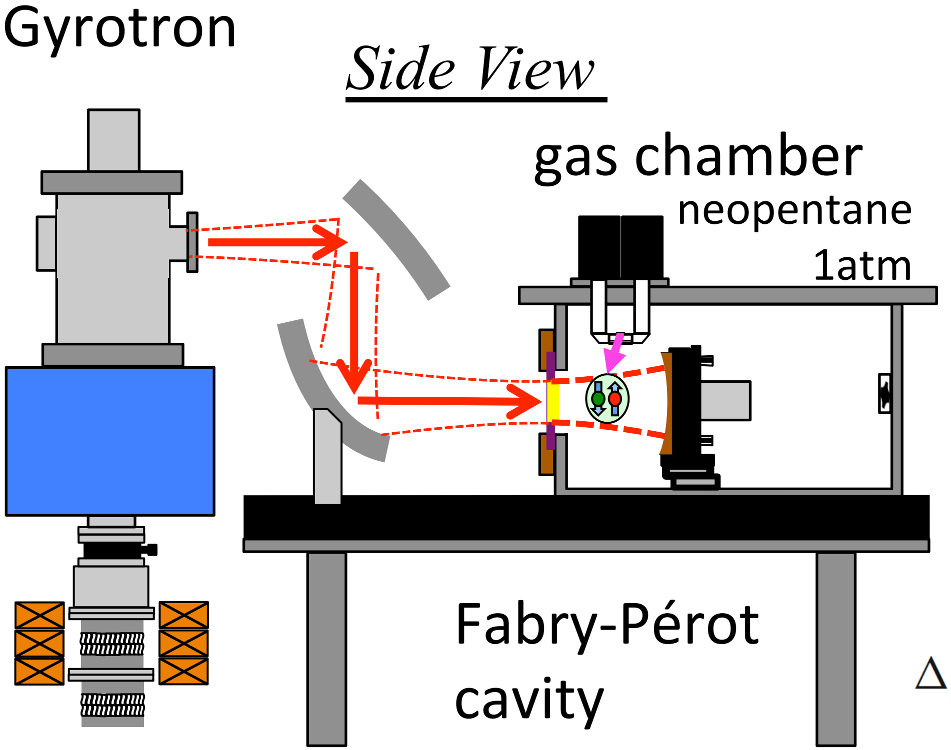
New Experiments (Tokyo)

- ➢ First millimeter-wave spectroscopy

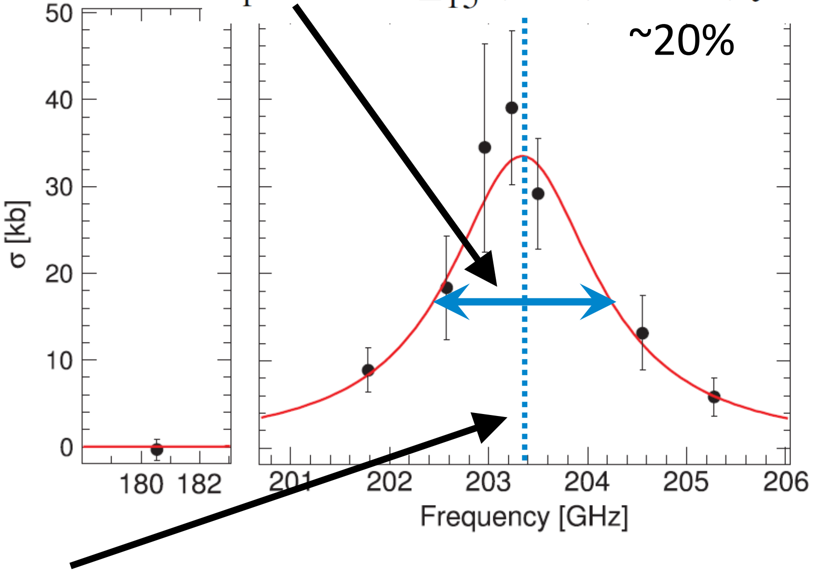
(A. Miyazaki *et al.*, PTEP **2015**, 011C01 (2015))

First direct measurement of HFS transition

using a frequency-tunable Gyrotron.



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

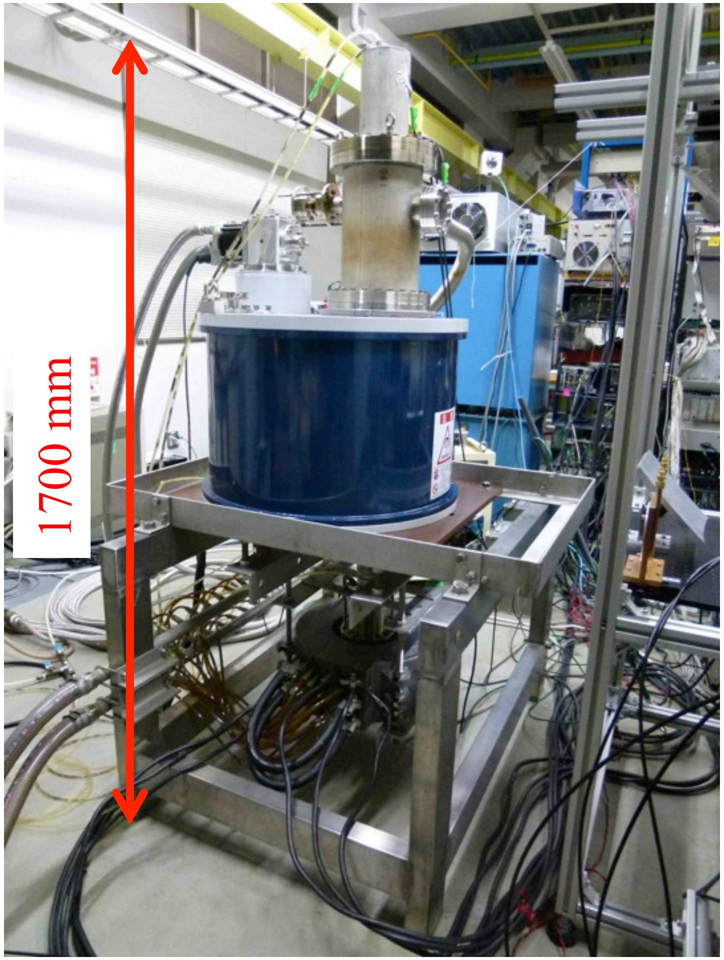


$$\Delta^{\text{HFS}}_{\text{Ps}} = 203.39^{+0.15}_{-0.14}\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{GHz}$$

~ 900 ppm

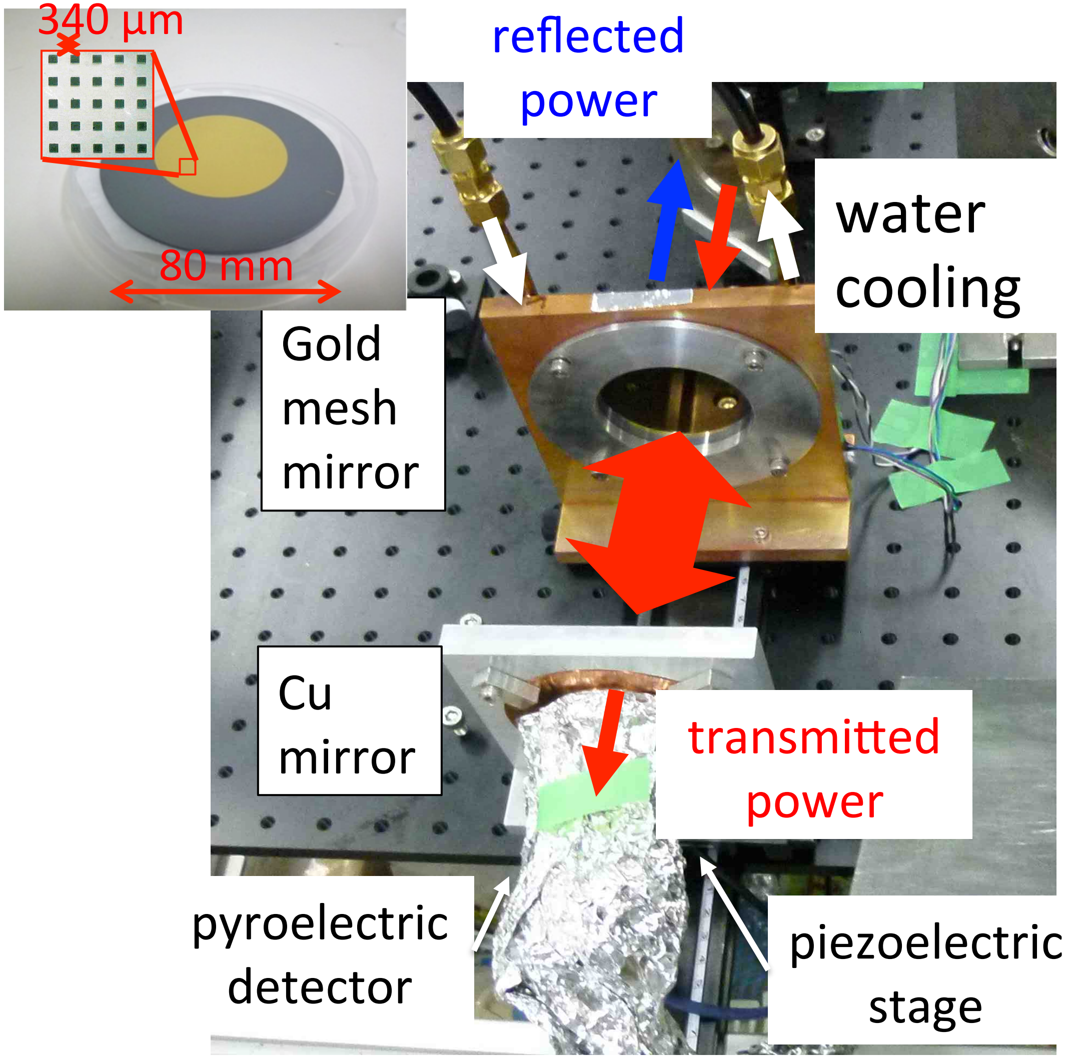
New Experiments (Tokyo)

Developed gyrotron collaboration with Fukui University (Japan)



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

Fabry-Pérot cavity



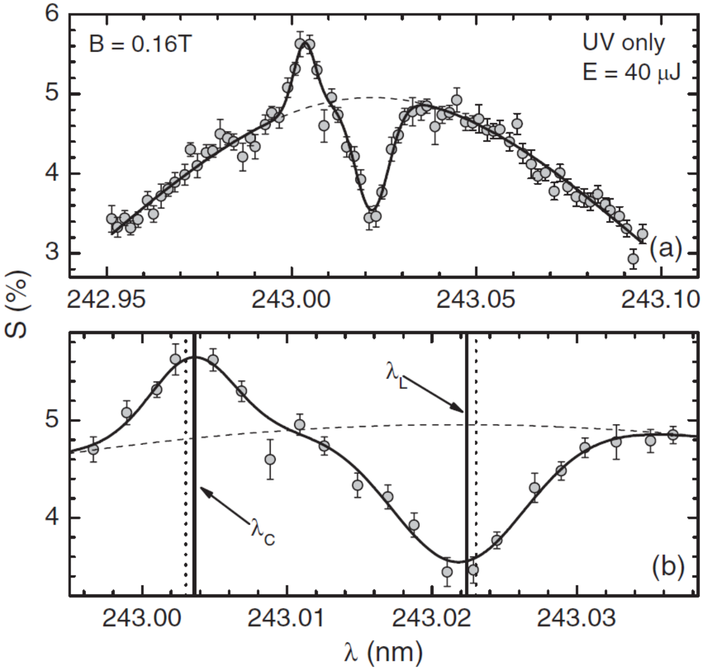
New Experiments (UC Riverside)

- Saturated Absorption Spectroscopy (SAS)

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

  Measure the 1S-2P (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 2P manifold.



$$\nu_{\rm hfs} = 2(\nu_C - \nu_L) \underbrace{+ (\nu_C + \nu_L)R,}_{\text{Recoil shift}}$$

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

~ 2%

Conclusion

- *Ps-HFS puzzle:* a large 4.5 σ discrepancy of Ps-HFS between the previous experimental values and theoretical calculation.
- Need to check the discrepancy with new techniques.
- New precise microwave spectroscopy using the Zeeman effect has been performed
  - ➢ Use 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 is 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).