Precise measurement of positronium hyperfine splitting using the Zeeman effect



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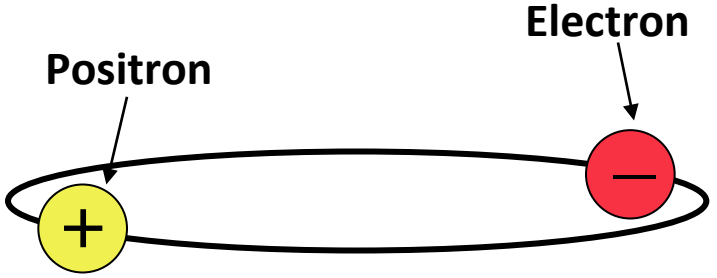
LEAP2011 @ TRIUMF 28/04/2011

Outline

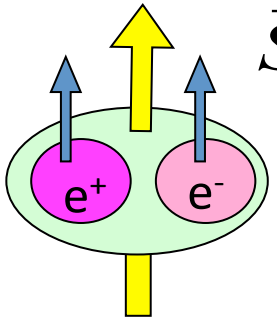
- Positronium Hyperfine Splitting (Ps-HFS)
- Our New Experiment
- Current Result
- Prospects

Positronium (Ps)

- Bound state of an electron (e^-) and a positron (e^+)
- Precision test of bound-state QED.



Lightest and Exotic Atom



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

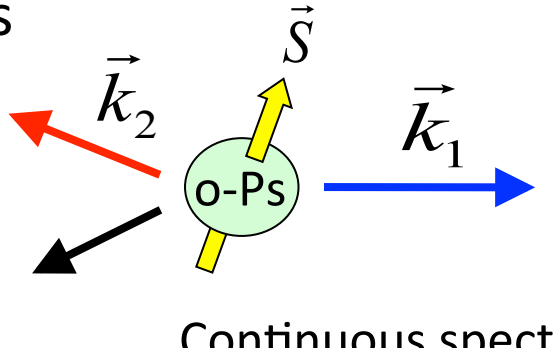
Ortho-positronium (o-Ps)

Spin=1 The same quantum number as photon

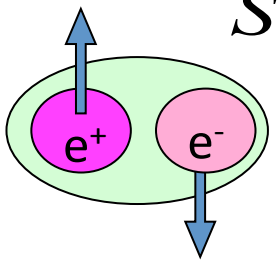
o-Ps → 3γ (, 5γ, …)

o-Ps

Lifetime 142 ns



Continuous spectrum



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

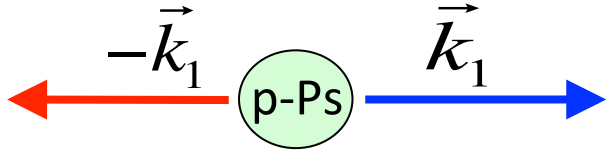
Para-positronium (p-Ps)

Spin=0 Scalar particle

p-Ps → 2γ (, 4γ, …)

p-Ps

Lifetime 125 ps

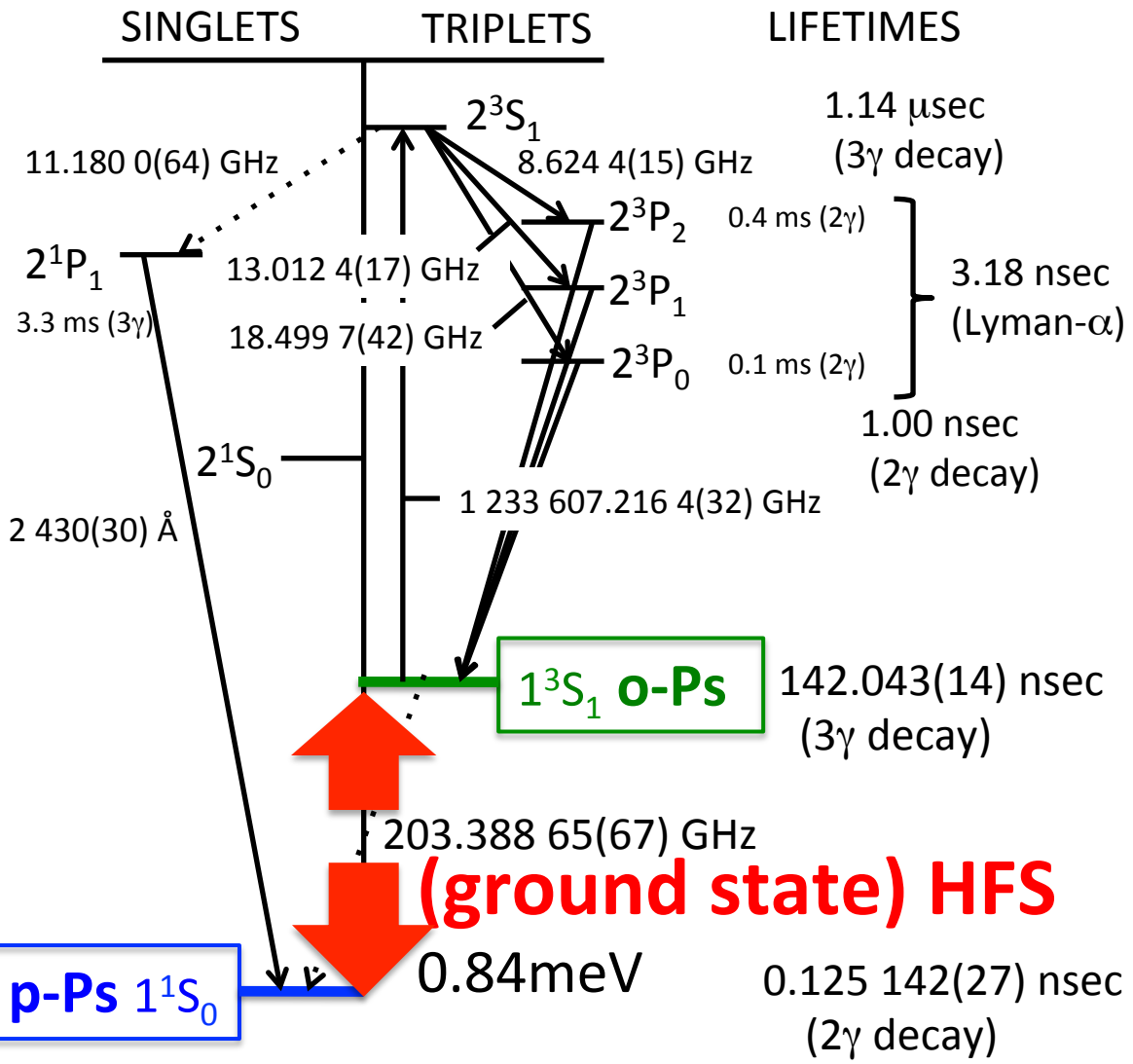


Monochromatic 511 keV

Positronium Hyperfine Splitting (Ps-HFS)

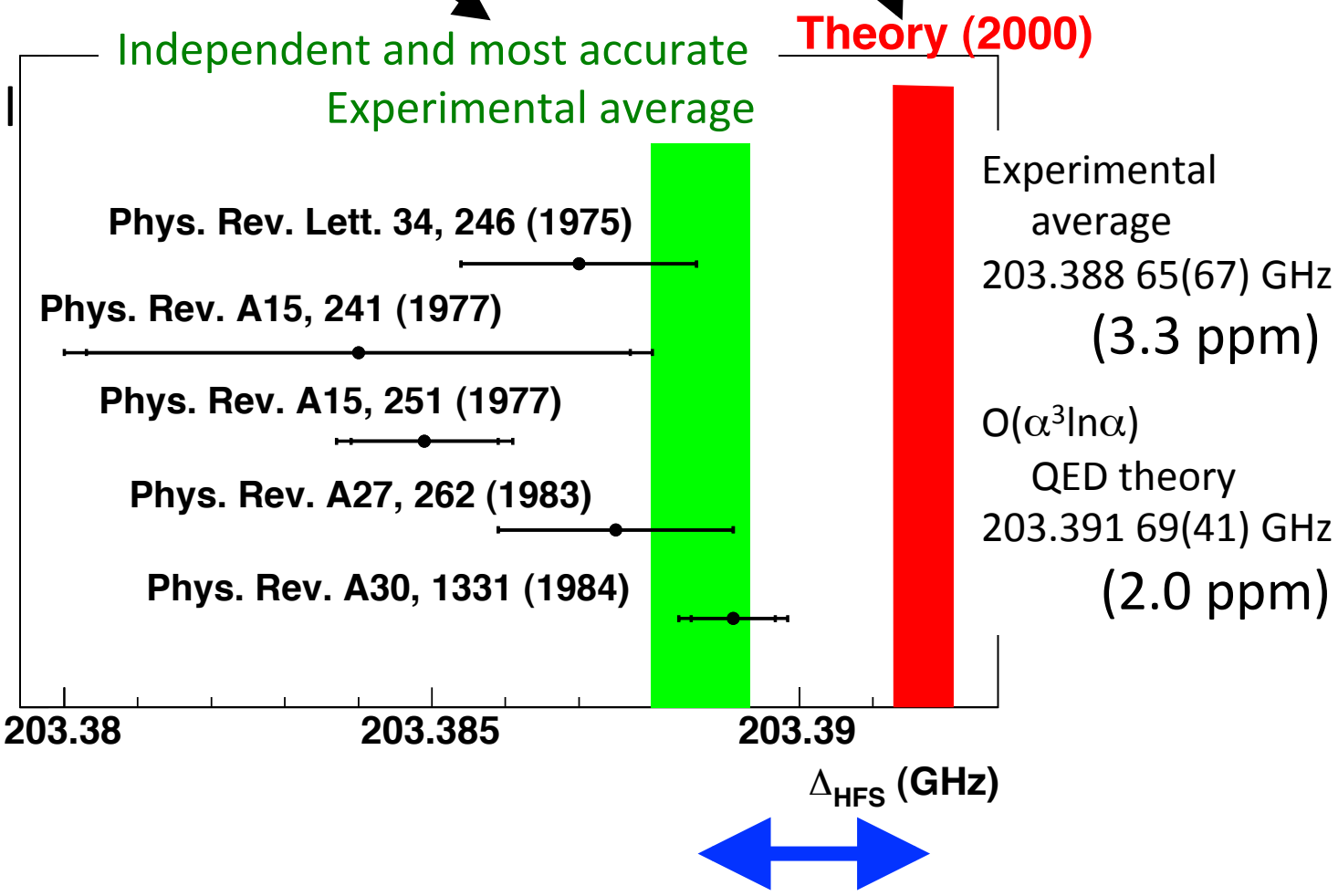
Energy difference between two spin eigenstates of the ground state Ps

→ Ps-HFS (203 GHz)



Discrepancy Between Experiments and Theory

Experimental results are consistently lower than theory.



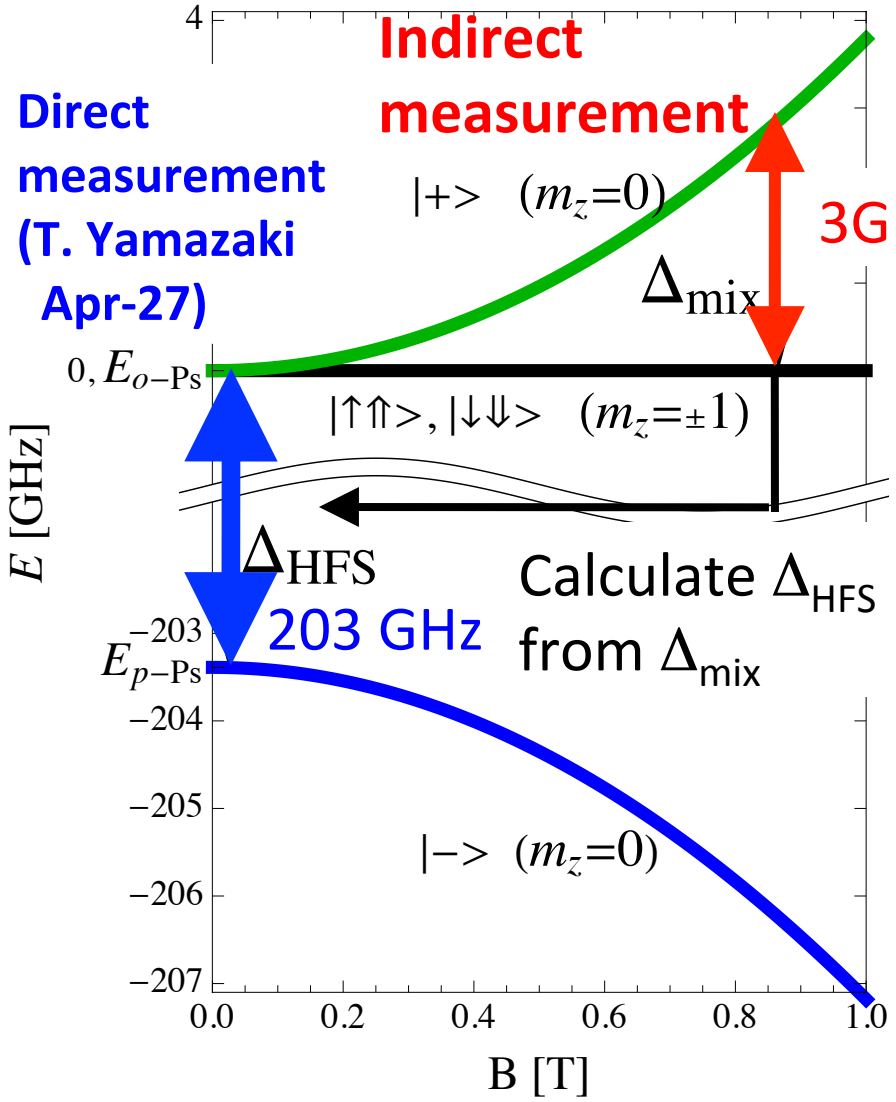
15 ppm (3.9 σ) significant discrepancy

Possible reasons for the discrepancy

- Common systematic uncertainties in the previous experiments
  - Underestimation of material effects. Unthermalized o-Ps can have a significant effect especially at low material density. *cf. o-Ps lifetime puzzle (1990's)*
  - Non-uniformity of the magnetic field. It is quite difficult to get ppm level uniform field in a large Ps formation volume.
- Need new development on calculation of bound-state QED or New physics beyond the Standard Model.

We have proposed new methods free from these systematic errors.
We will provide an independent check for the discrepancy.

Experimental Technique
Indirect Measurement using Zeeman Effect



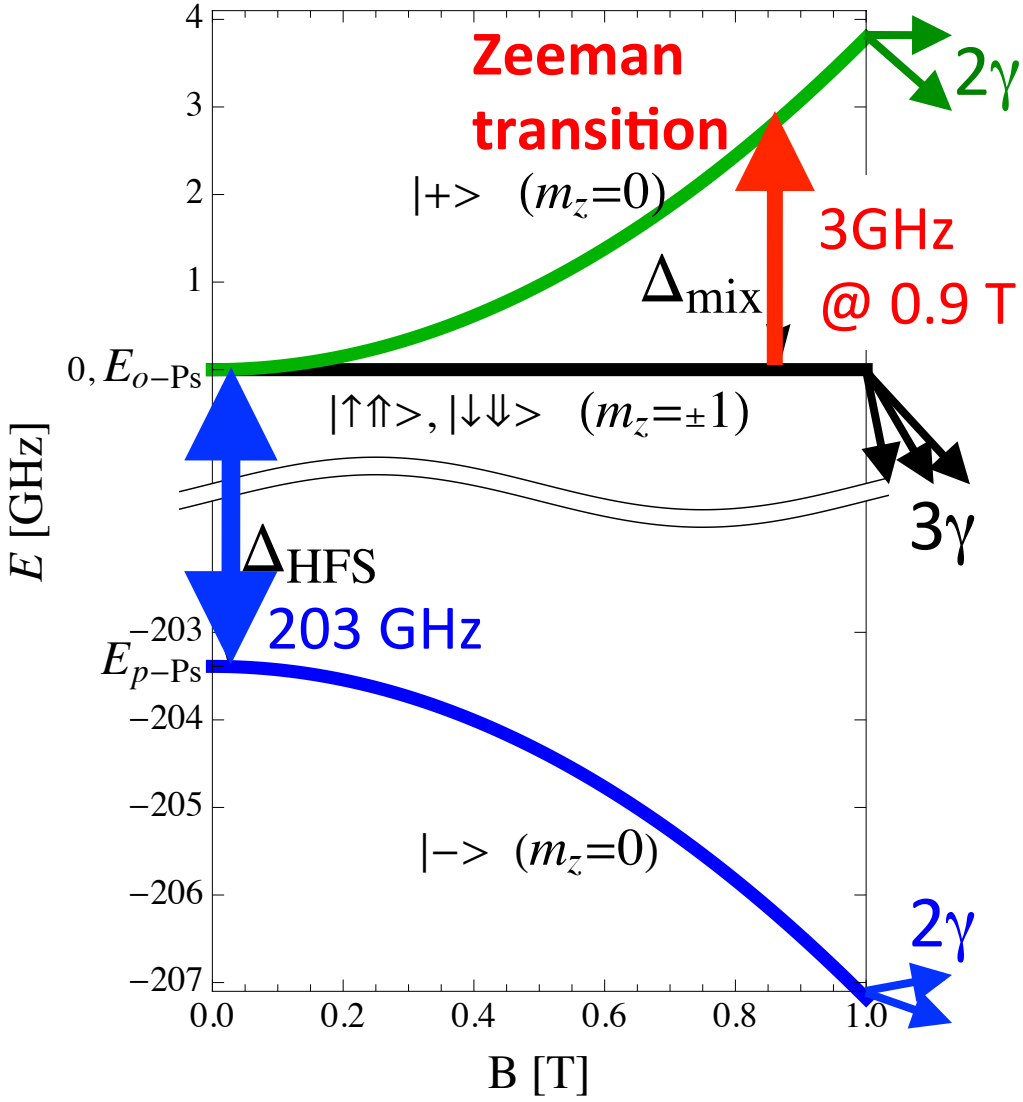
In a static magnetic field, the **p-Ps** state mixes with the **m_z=0 state of o-Ps** (Annihilate into 2 γ-rays).

Precisely measure the Δ_{mix} and calculate Δ_{HFS} by the equation,

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

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

Experimental Technique
Indirect Measurement using Zeeman Effect



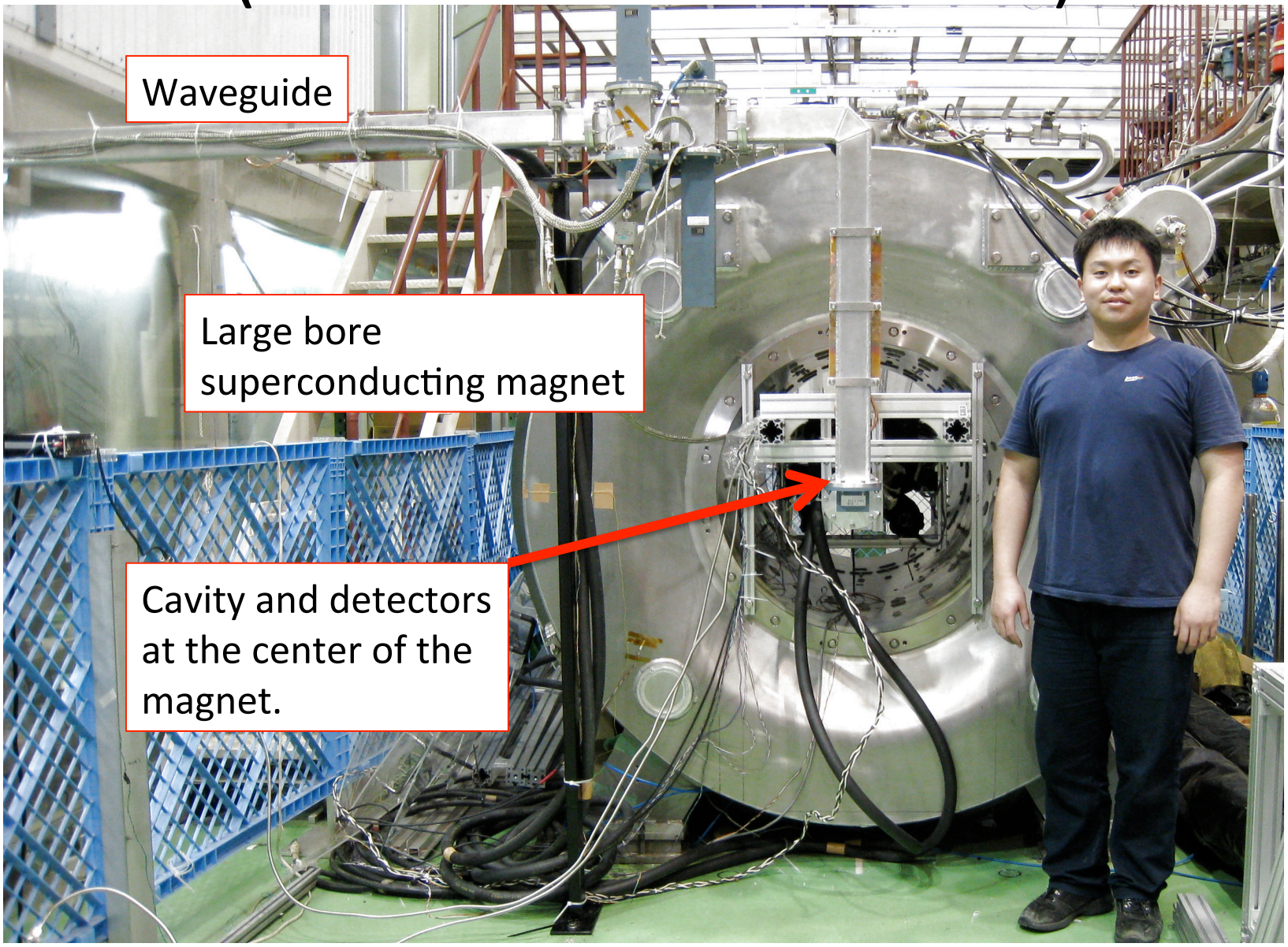
When a microwave field with a frequency of Δ_{mix} is applied, transitions between the m_z=0 and m_z=±1 states of o-Ps are induced.

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

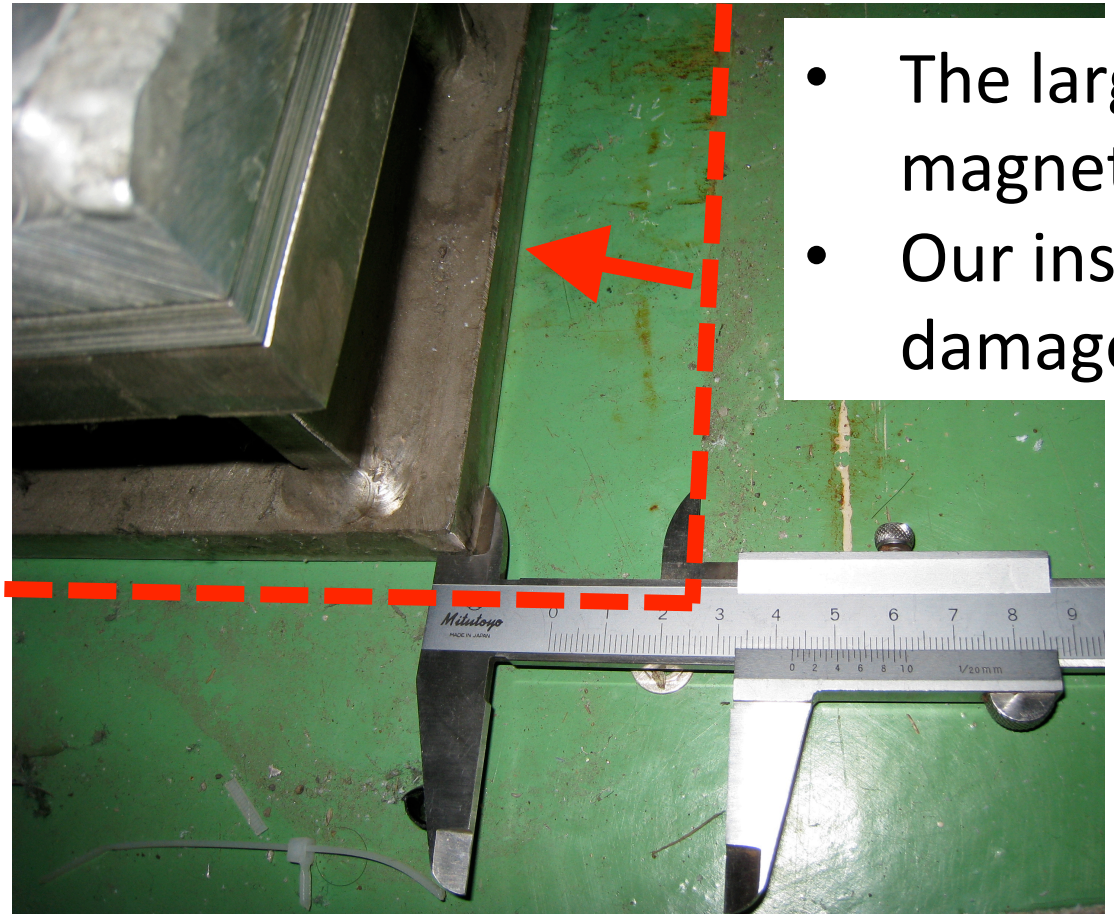
This increase is our experimental signal.

→This is the same approach as previous experiments.

Measurement @ KEK (Jul 2010 – 11 Mar 2011)



Earthquake on 11 Mar 2011

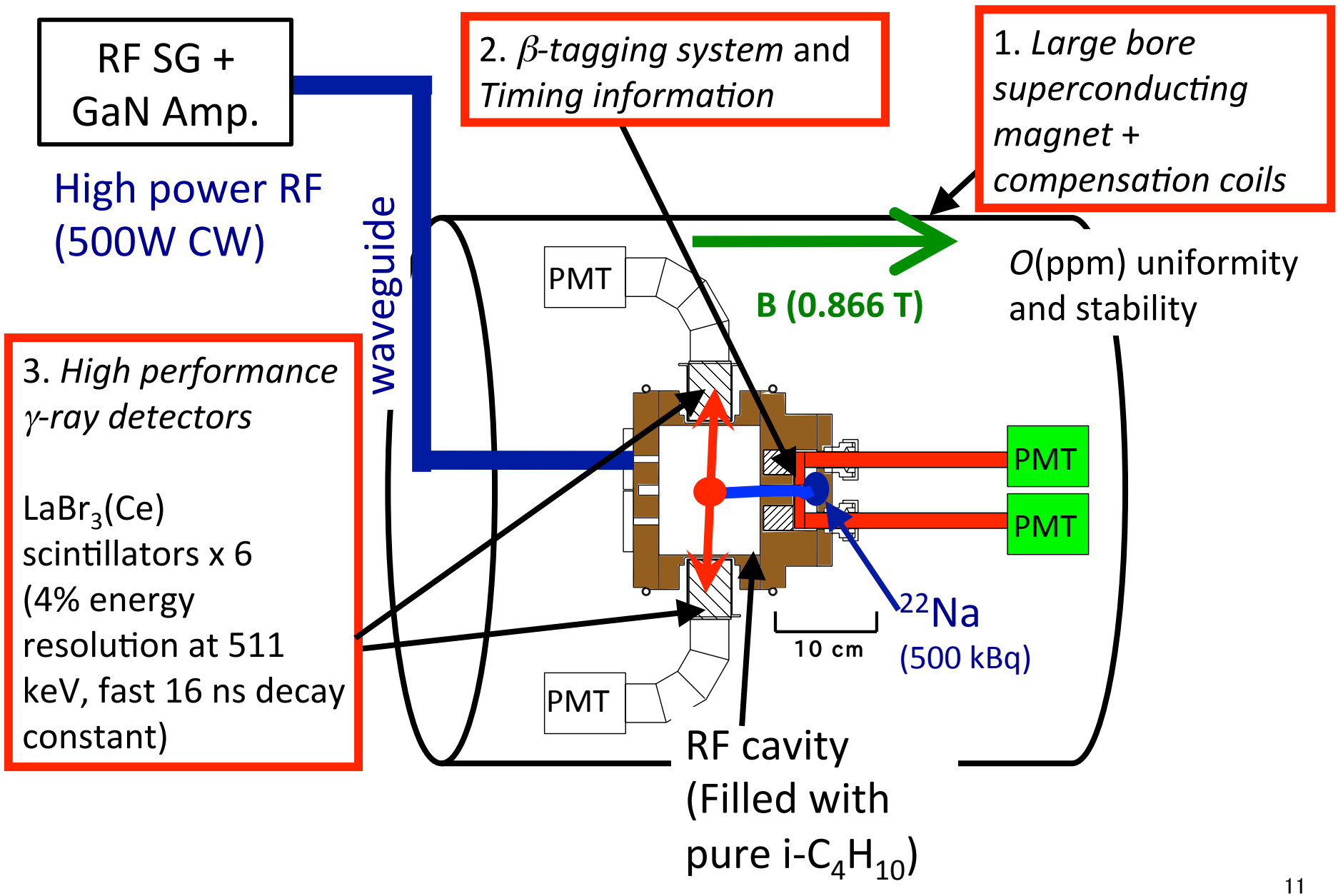


- The large bore superconducting magnet (13 t) moved 4.3 cm.
- Our instruments were not damaged.

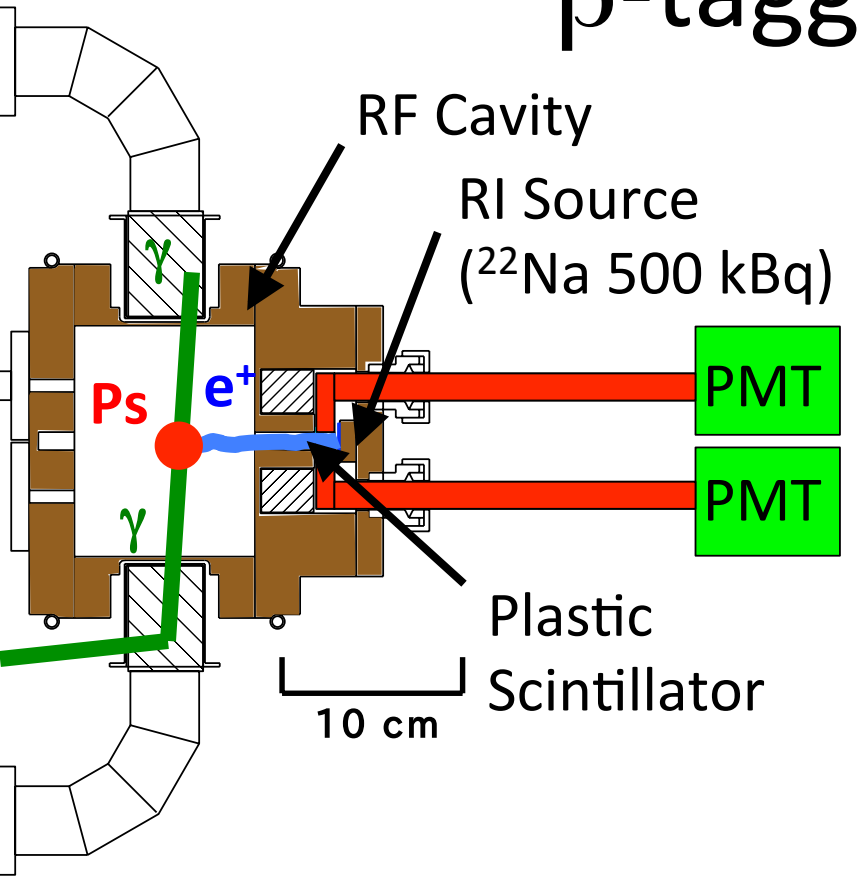


- Due to lack of electric power supply, we now stop measurement.

Our new Experiment



β-tagging system

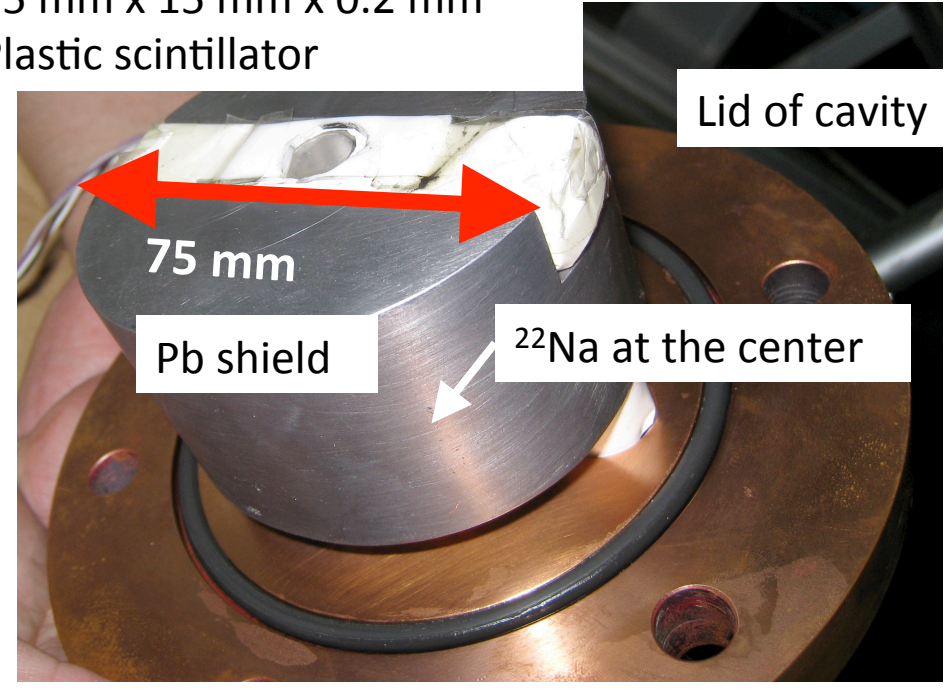


- Tag e^+ from the ^{22}Na by thin (0.2 mm) plastic scintillator.

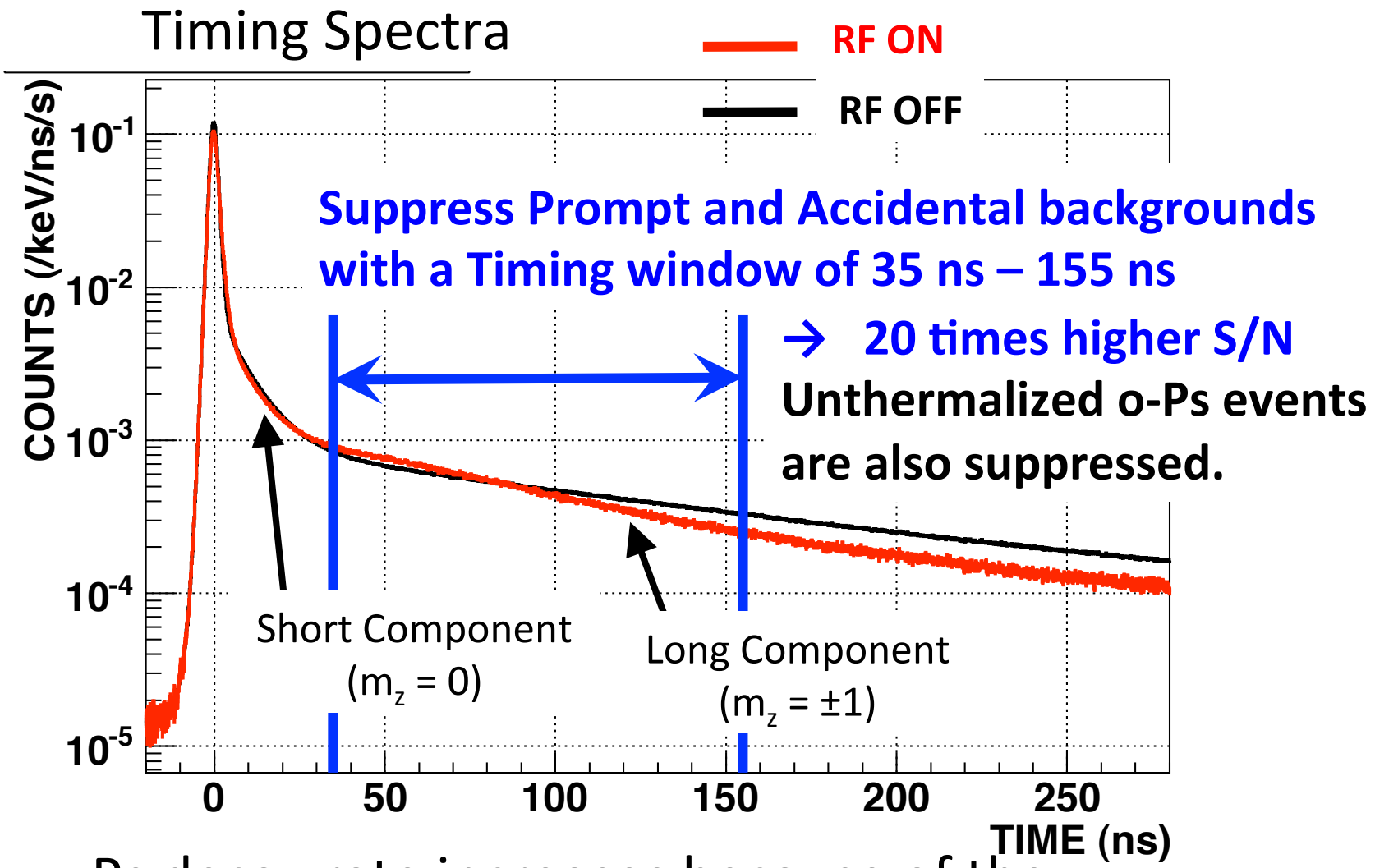
  → *t=0*

- DAQ Trigger is made by coincidence of e^+ tag signal and γ-ray detection.
- Time difference of these signals is Ps life time of each event.

15 mm x 15 mm x 0.2 mm
Plastic scintillator

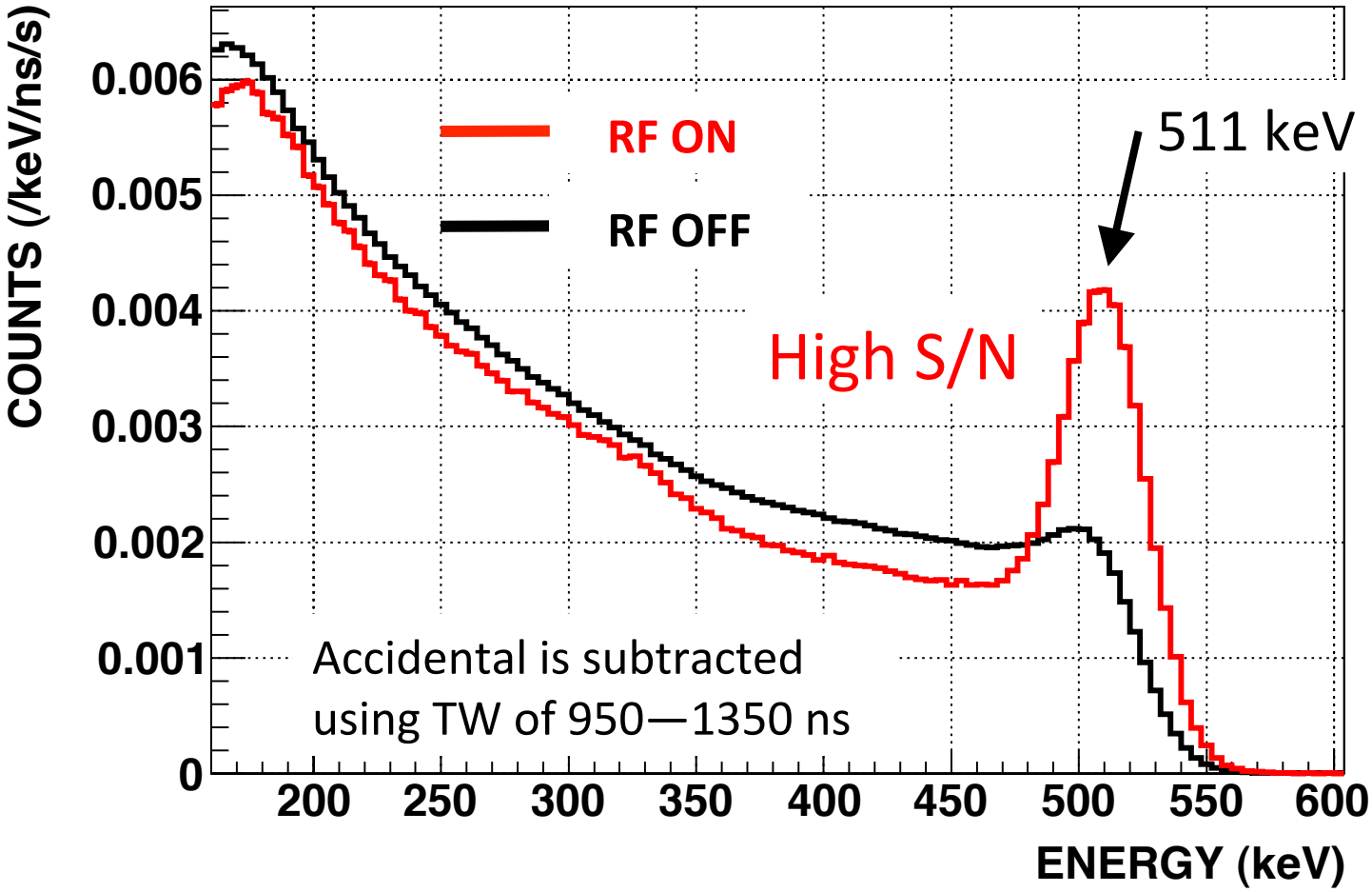


Analysis (Timing Spectra)



Ps decay rate increases because of the Zeeman transition.

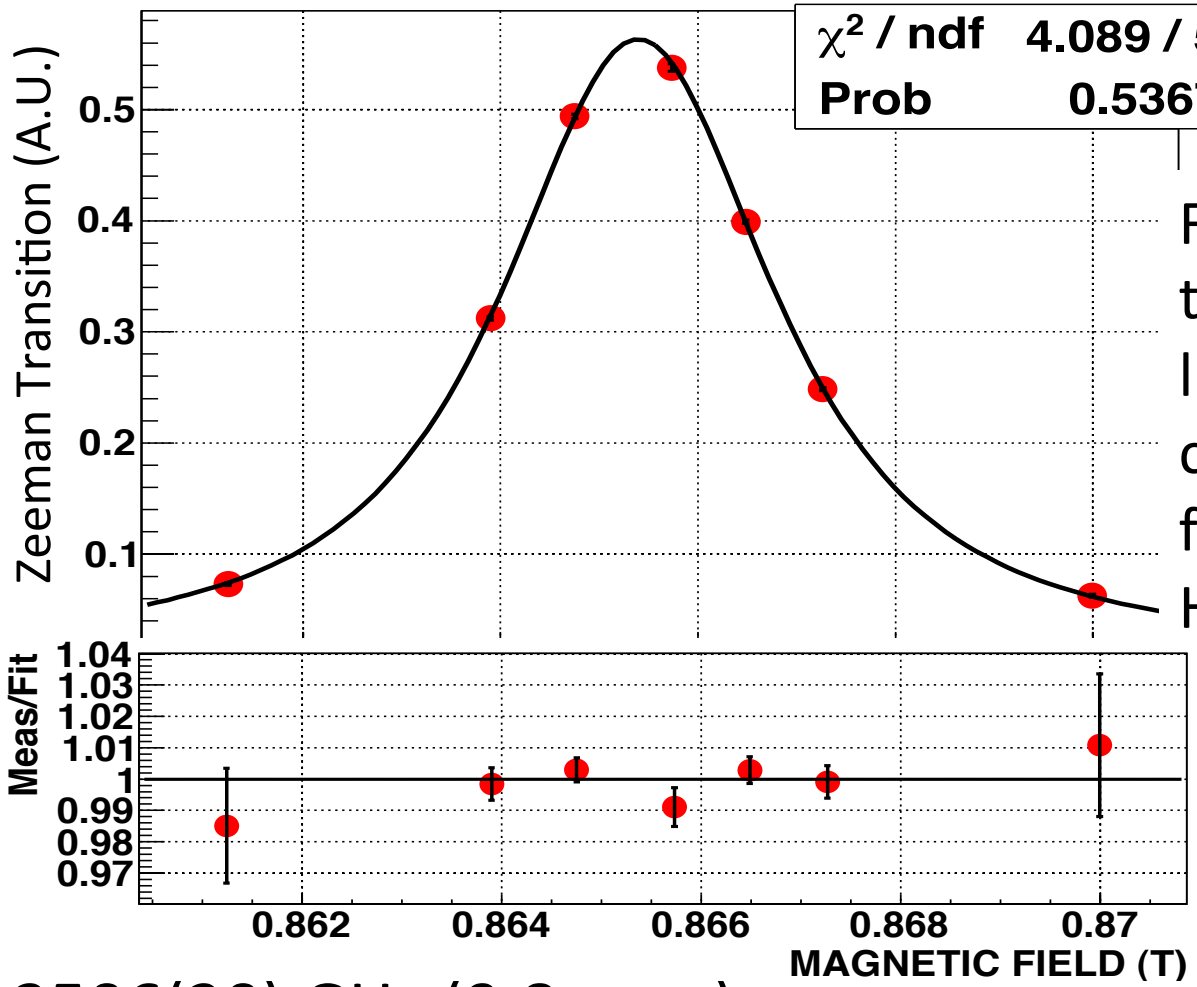
Analysis (Energy Spectra)



2γ decay rate increases because of the Zeeman transition. Zeeman transition probability is calculated from the difference between RF-ON and RF-OFF.

Resonance Line (0.895 amagat)

Scanned by Magnetic Field with the fixed RF frequency and power.

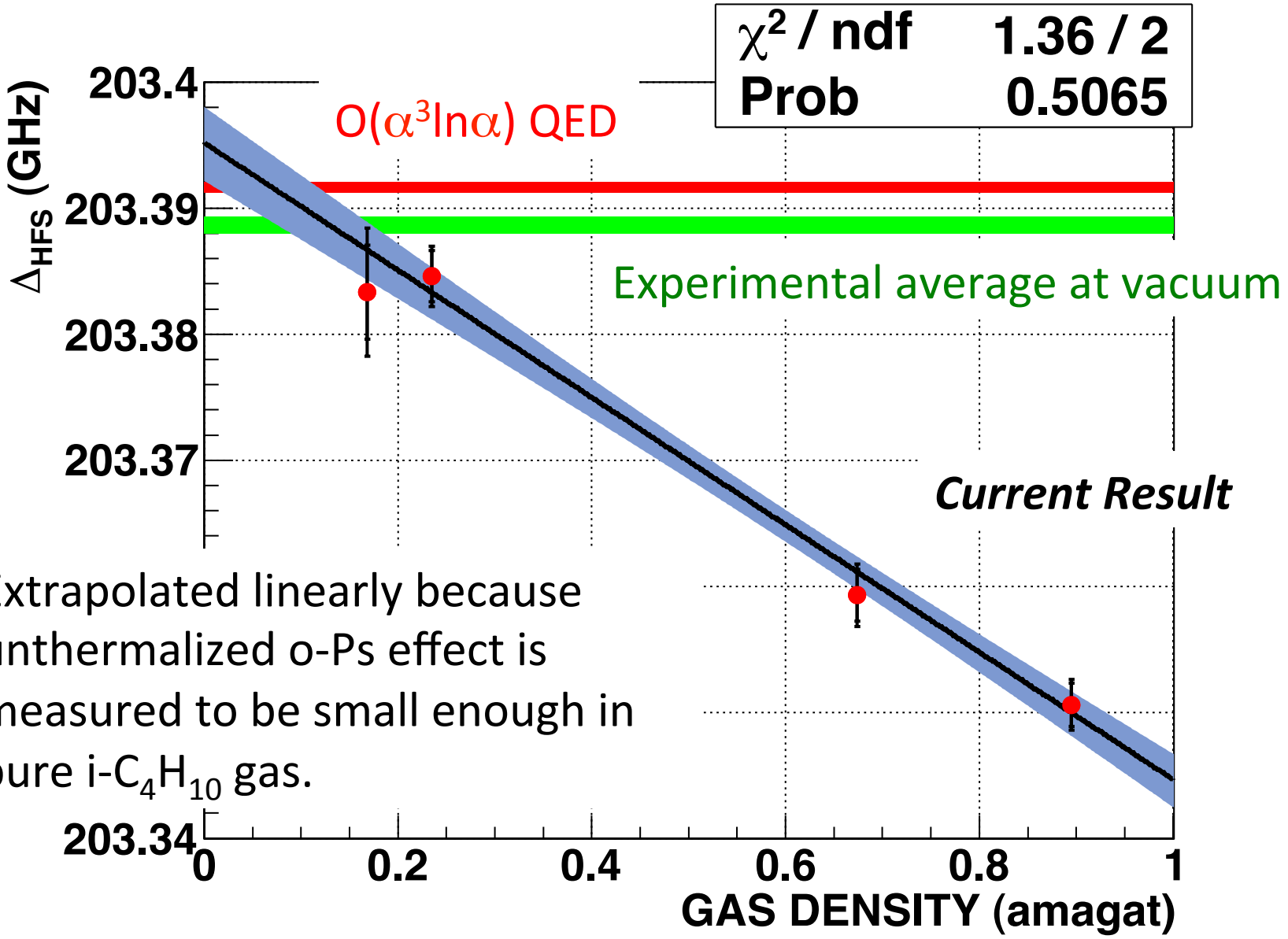


Fitted by theoretical line calculated from Hamiltonian

Δ_{HFS} = 203.3506(20) GHz (9.8 ppm) (Including errors from MC stat. ,P, and Q)

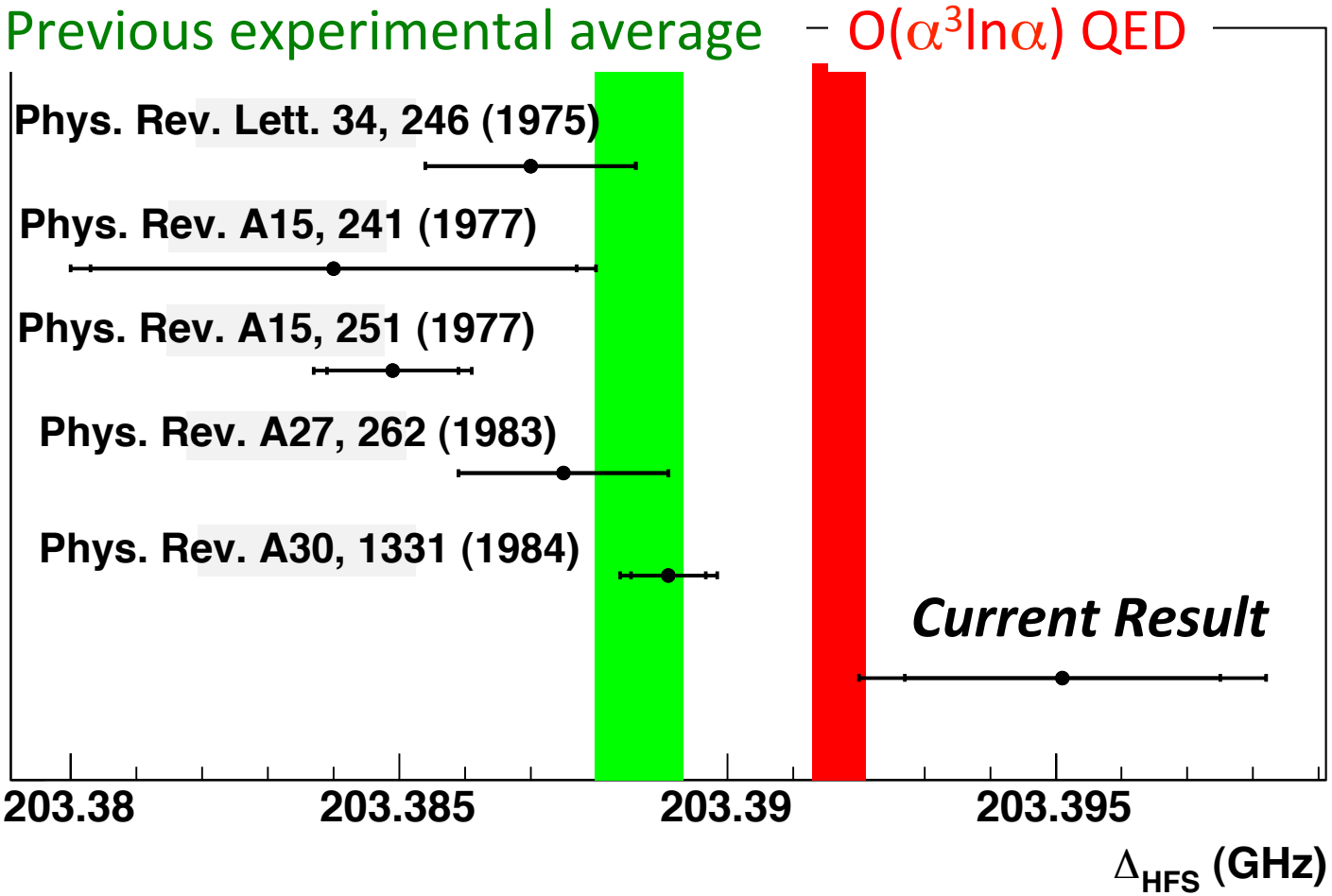
→ Obtain the Δ_{HFS} in vacuum with density correction.

Gas Density Dependence



Extrapolated linearly because unthermalized o-Ps effect is measured to be small enough in pure i-C_4H_{10} gas.

Current Result



Preliminary value :

Δ_{HFS} = 203.3951 ± 0.0024 (stat., 12ppm)

± 0.0019 (sys., 9.5 ppm) GHz

Systematic Errors (Current result)

	Source	ppm in Δ_{HFS}
Magnetic field	Non-uniformity	1.8
	Offset and reproducibility	1.0
	NMR measurement	1.0
Detection efficiency	Estimation using MC simulation	7.0
Material effect	Ps thermalization	3.0
RF	RF Power	2.9
	Q_L value of RF cavity	4.3
	RF frequency	1.0
	Quadrature sum	9.5

Prospects

- Material Effect: Currently we assumed that HFS depends on gas density linearly. If the unthermalized Ps contribution is large, the dependence is not linear. According to previous thermalization measurement (Skalsey et al.), thermalization effect is estimated to be less than 3 ppm with i-C_4H_{10} gas. We are now precisely measuring the Ps thermalization using different technique.
- RF System: The experimental environment (temperature) control → O(ppm) uncertainty
- Detection efficiency: Currently it is estimated by Monte Carlo simulation. It will be carefully studied and will be estimated by real data. → O(ppm) uncertainty
- Statistics: 12 ppm has been obtained.

A measurement with a precision of O(ppm) is expected within a year.

Conclusion

The current result of

HFS = 203.3951 ± 0.0024 (stat., 12 ppm)
± 0.0019 (sys., 9.5 ppm)

has been obtained so far.

- Our experiment is free from possible common uncertainties in previous experiments (Non-uniformity of magnetic field, Ps thermalization effect).
- A new result with an accuracy of O(ppm) will be obtained within a year which will be an independent check of the discrepancy.