Precise Measurement of Hyperfine Splitting of Positronium using Zeeman Effect

A. Ishida[1], G. Akimoto[1], Y. Sasaki[1],

T. Suehara[2], T. Namba[2], S. Asai[1], T. Kobayashi[2],

H. Saito[3], M. Yoshida[4], K. Tanaka[4], A. Yamamoto[4]

[1]Department of Physics, the University of Tokyo

[2]International Center for Elementary Particle Physics (ICEPP), the University of Tokyo

[3]Department of General Systems Studies, the University of Tokyo

[4]High Energy Accelerator Research Organization (KEK)

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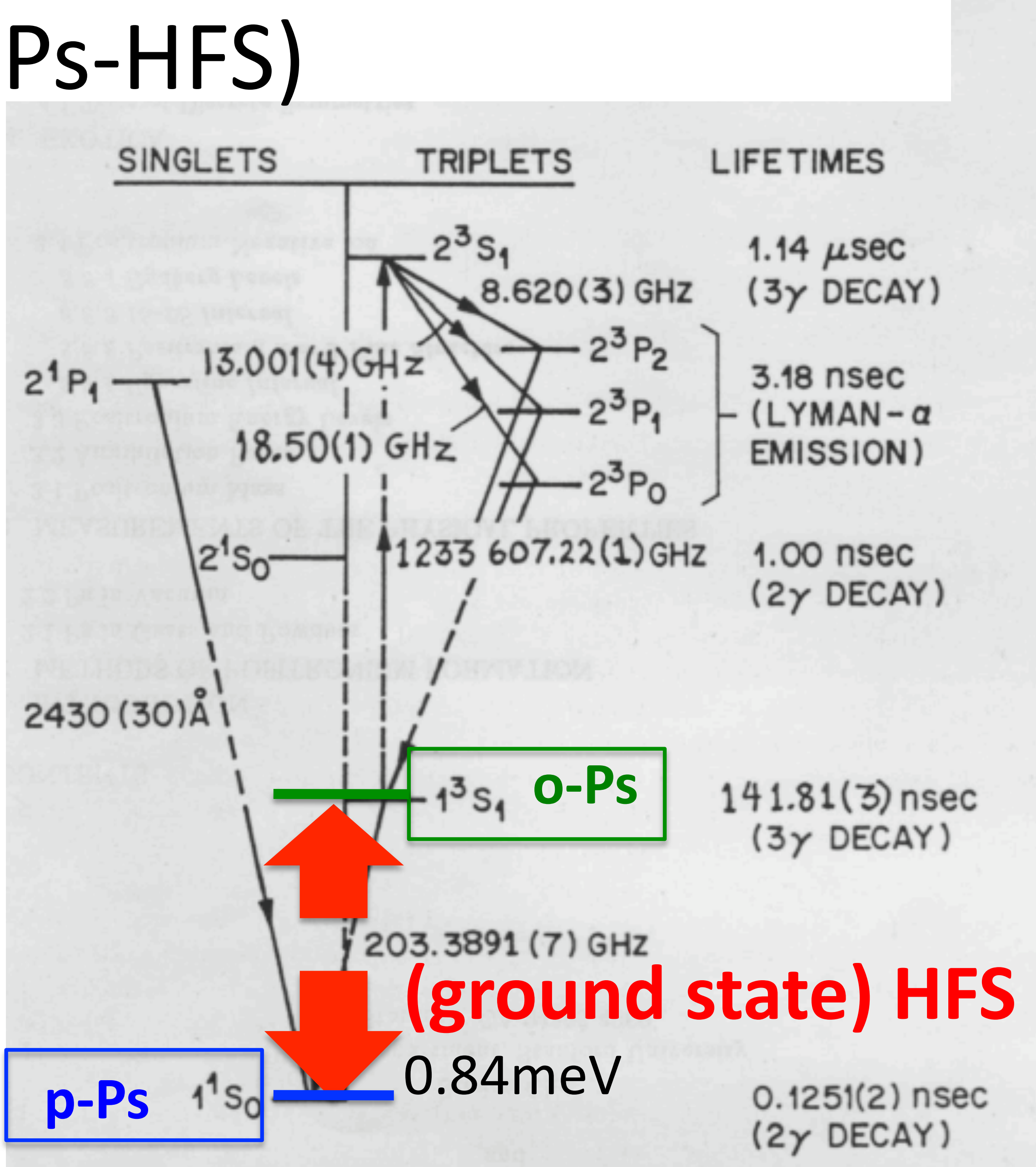
Outline

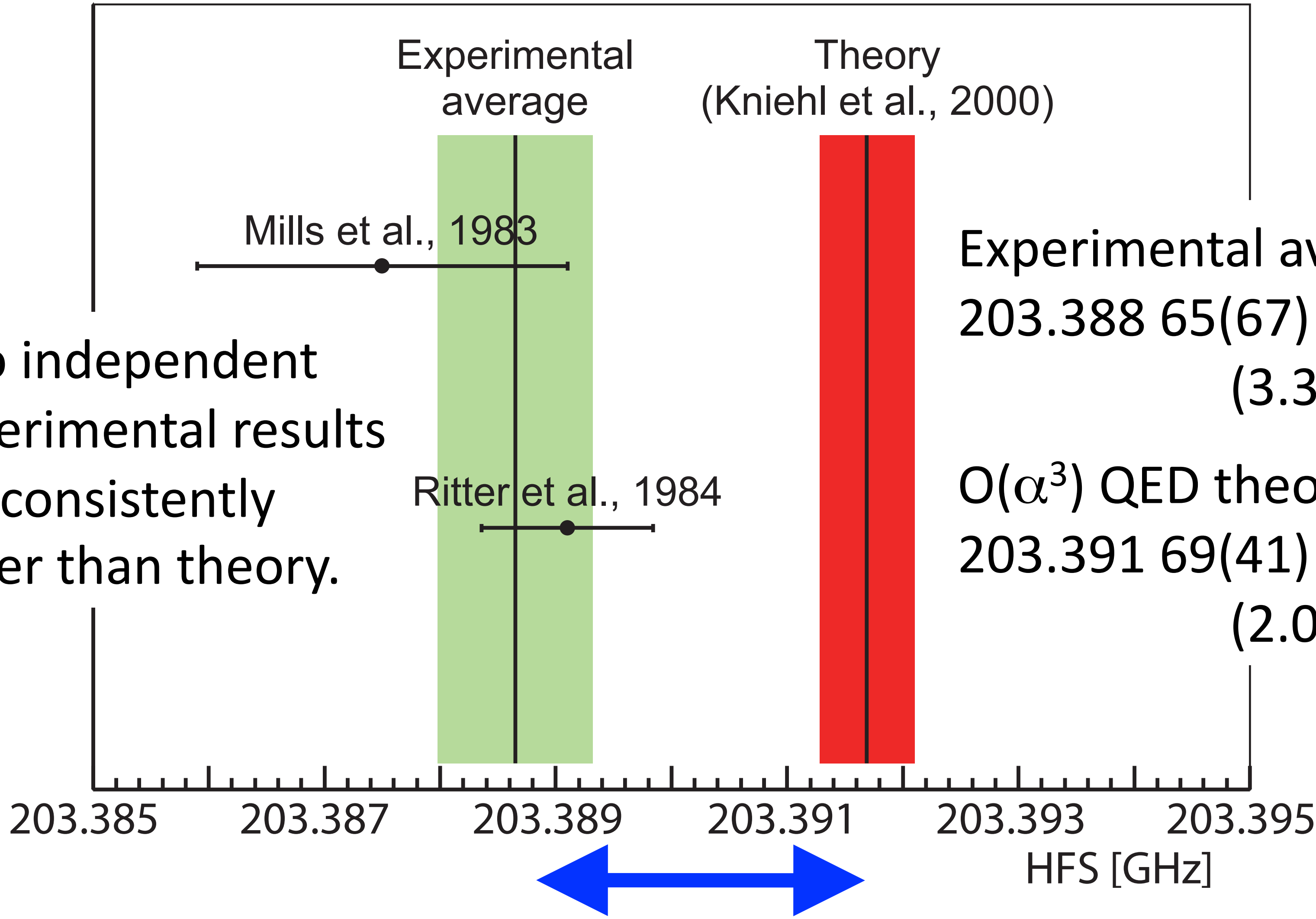
- Positronium Hyperfine Splitting (Ps-HFS)
- Our new experiment
- Results of the prototype run
- Prospects & Current status

Positronium Hyperfine Splitting (Ps-HFS)

Energy difference between two spin eigenstates of the ground state Ps → Ps-HFS



Discrepancy Between Experiments and Theory



Two independent experimental results are consistently lower than theory.

Experimental average
203.388 65(67) GHz
(3.3 ppm)

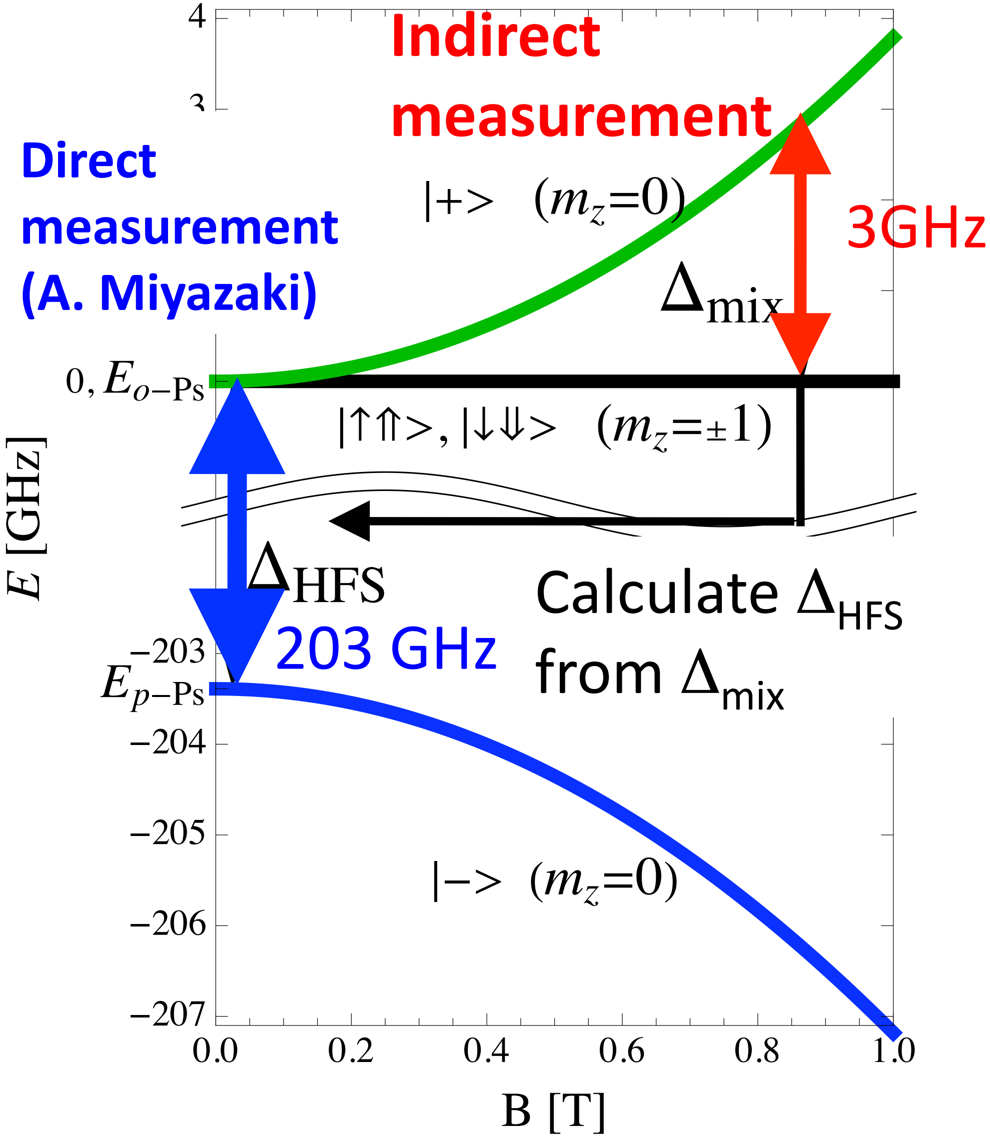
$O(\alpha^3)$ QED theory
203.391 69(41) GHz
(2.0 ppm)

15 ppm (3.9 σ) 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.
- Mistakes in the theoretical calculations
  - The bound state QED is still developing. ($O(\alpha^3)$ calculation)
  - Non-relativistic QED (NRQED) might be wrong.
- New physics beyond the Standard Model

Experimental Technique
Indirect Measurement using Zeeman Effect



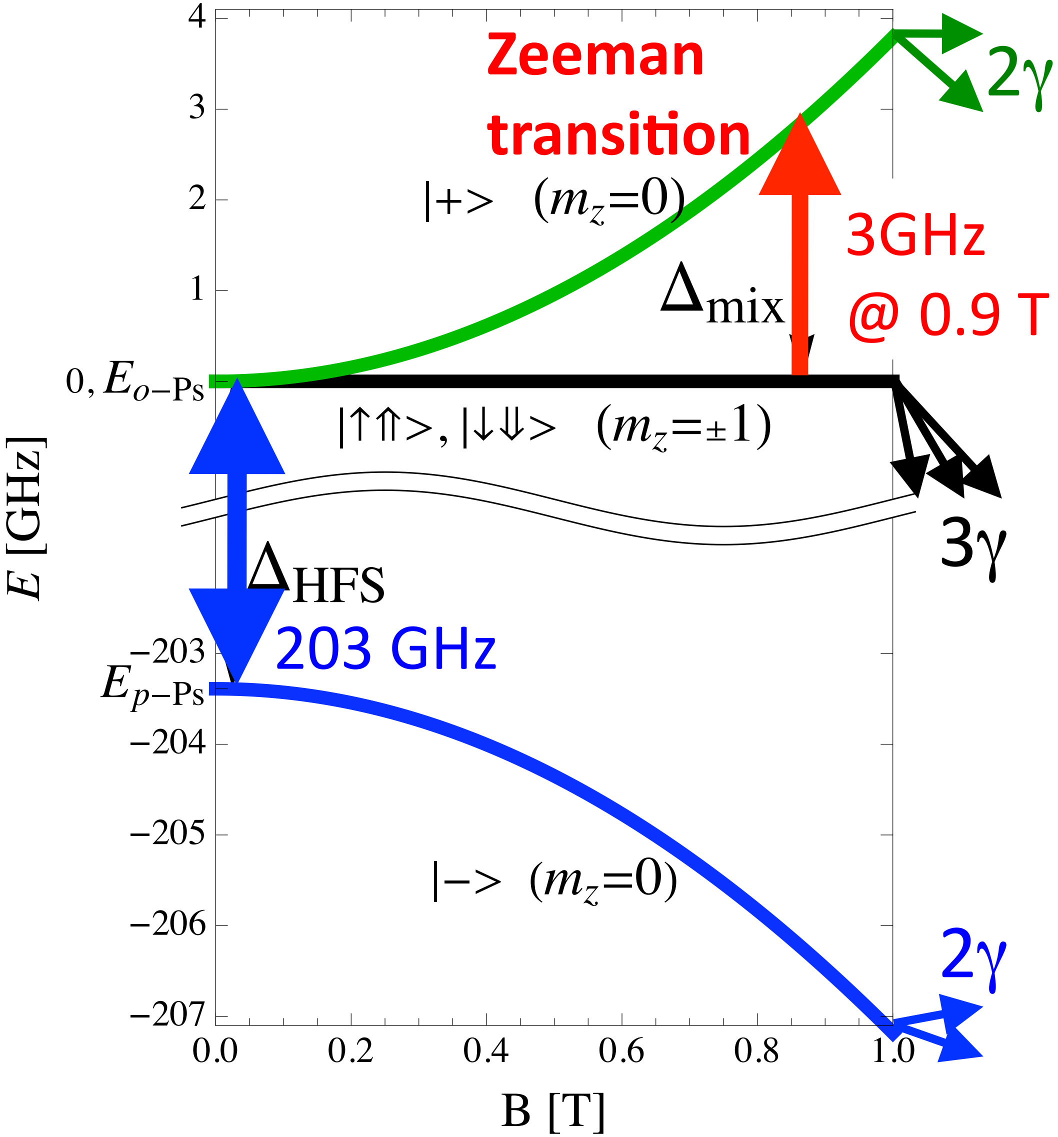
In a static magnetic field, the **p-Ps** state mixes with the **m_z=0 state of o-Ps** (Annihilate into 2 γ-rays).

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



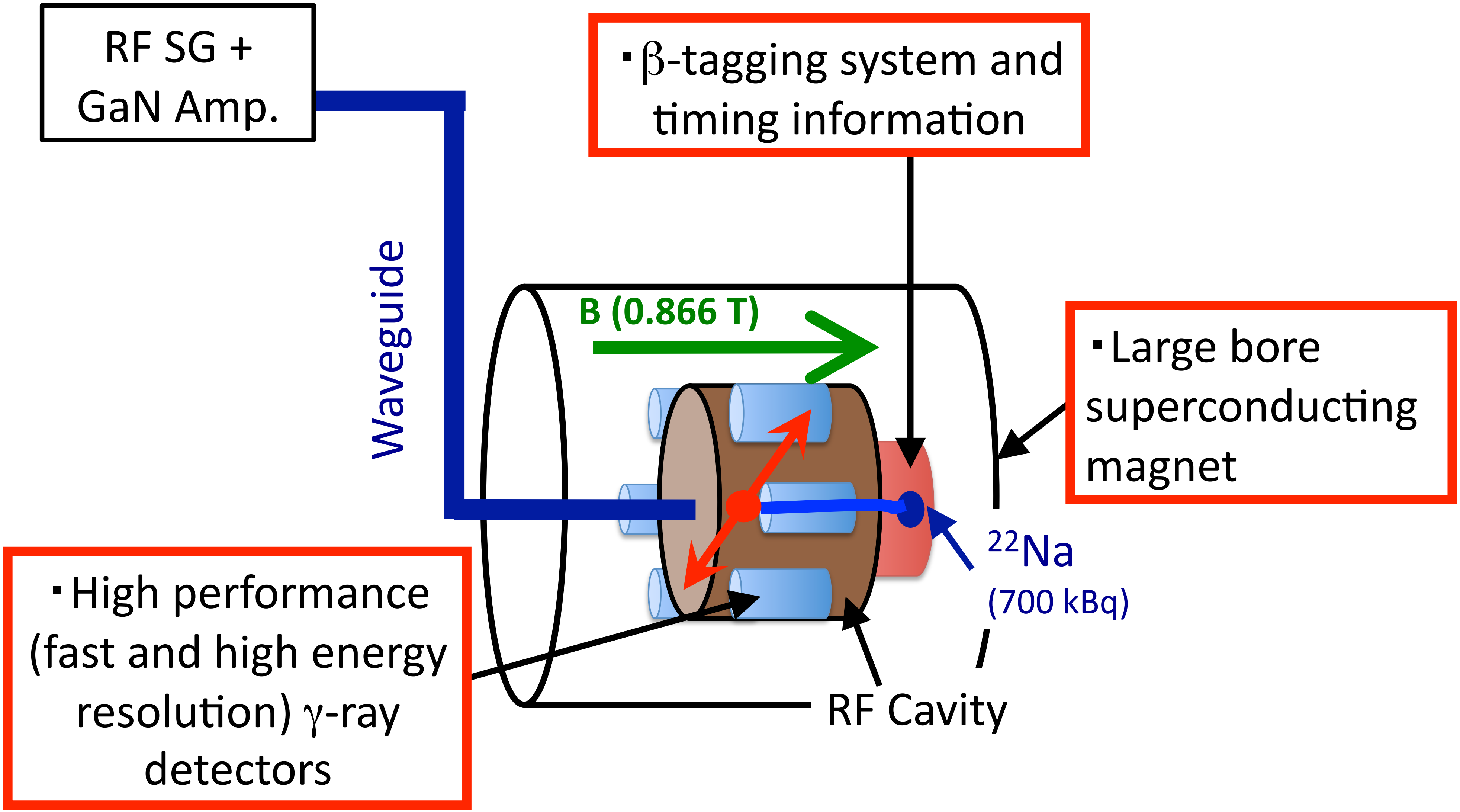
When a microwave field with a frequency of Δmix is applied, transitions between the m_Z=0 and m_Z=±1 states of o-Ps are induced.

→ 2γ-ray annihilation (**511 keV monochromatic signal**) rate increases.
This increase is our experimental signal.

→This is the same approach as previous experiments.

Our New Experiment

To reduce the systematic uncertainties, we use the following new methods.



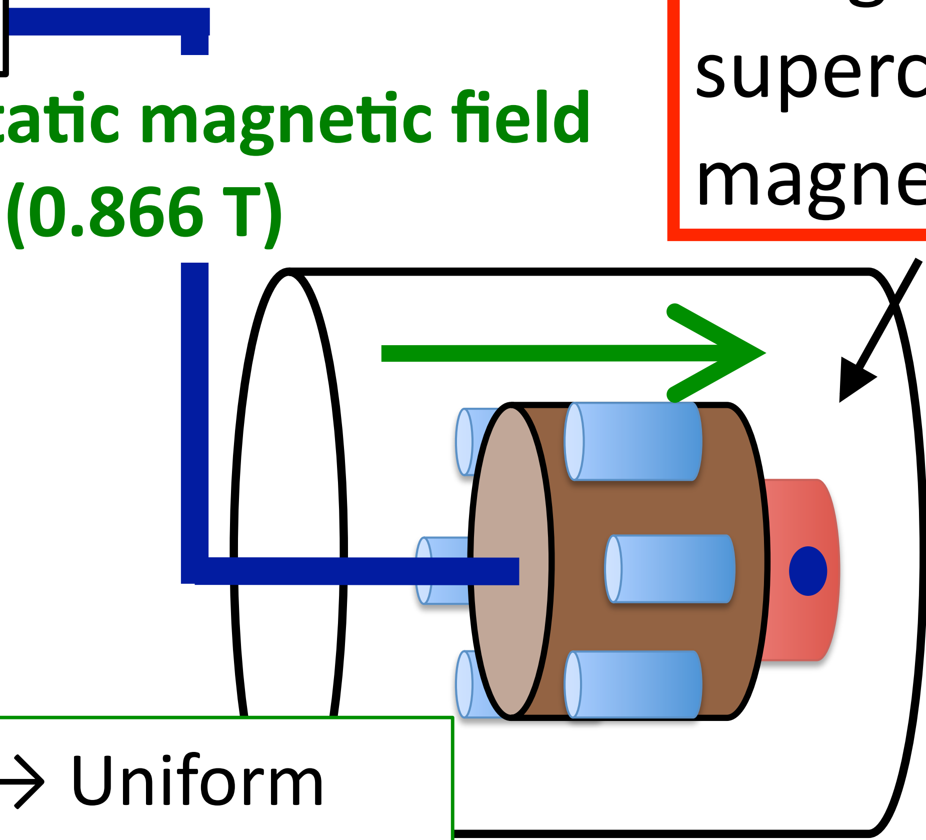
Our New Experiment

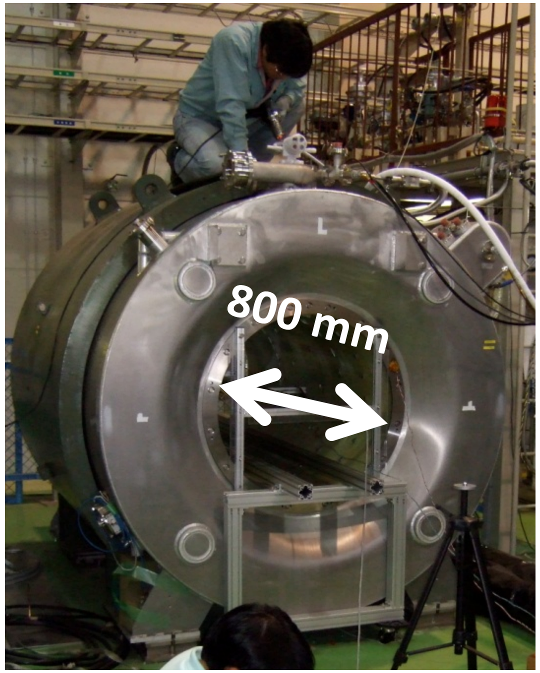
To reduce the systematic uncertainties, we use the following new methods.

RF SG +
GaN Amp.

Static magnetic field
B (0.866 T)

▪ Large bore superconducting magnet





Large size → Uniform
Persistent Current mode
→ Stable

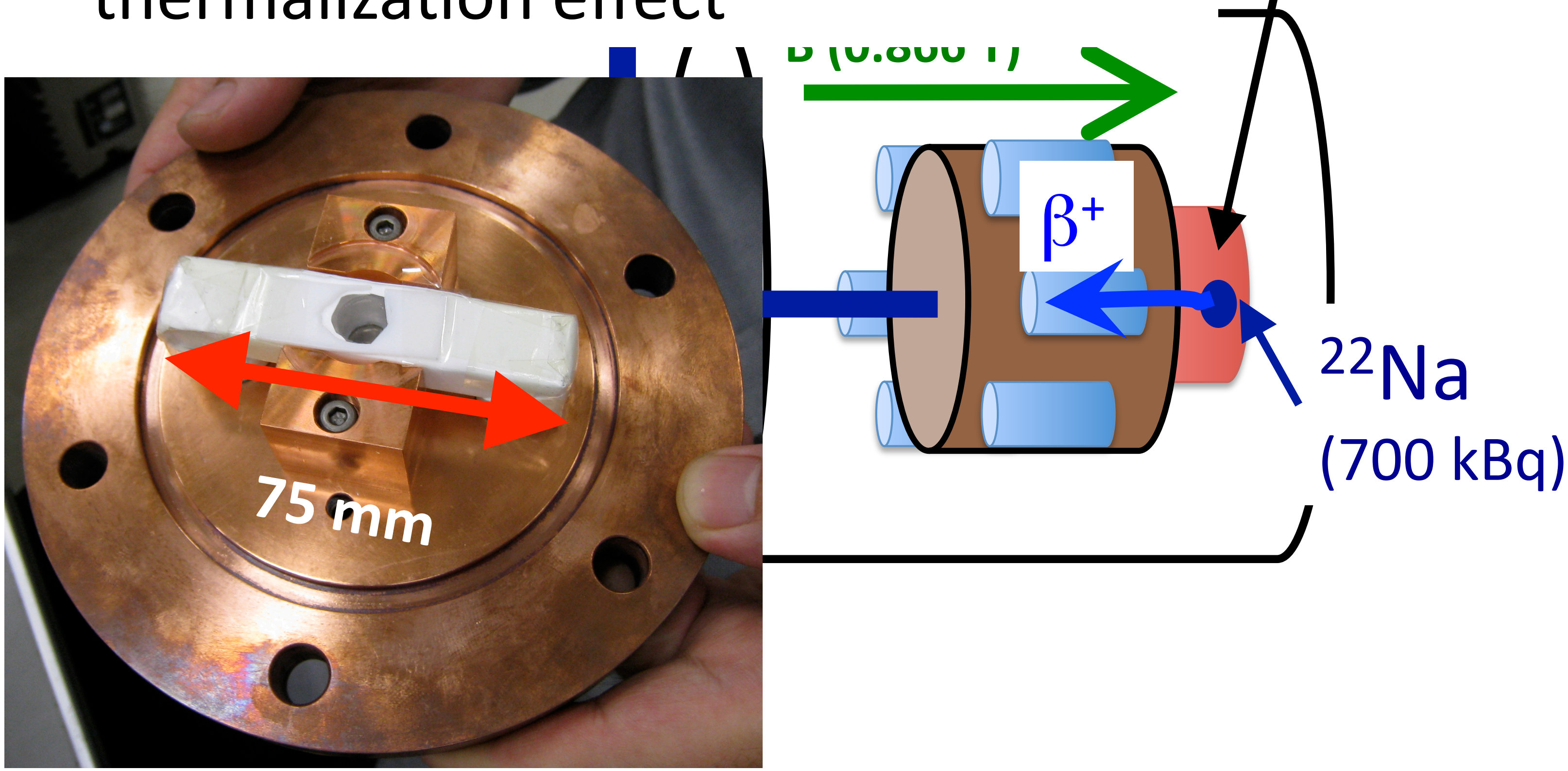
Our New Experiment

To reduce the systematic uncertainties, we use the following new methods.

- β-tagging system and timing information

(1) Prompt suppression (→ Next page)

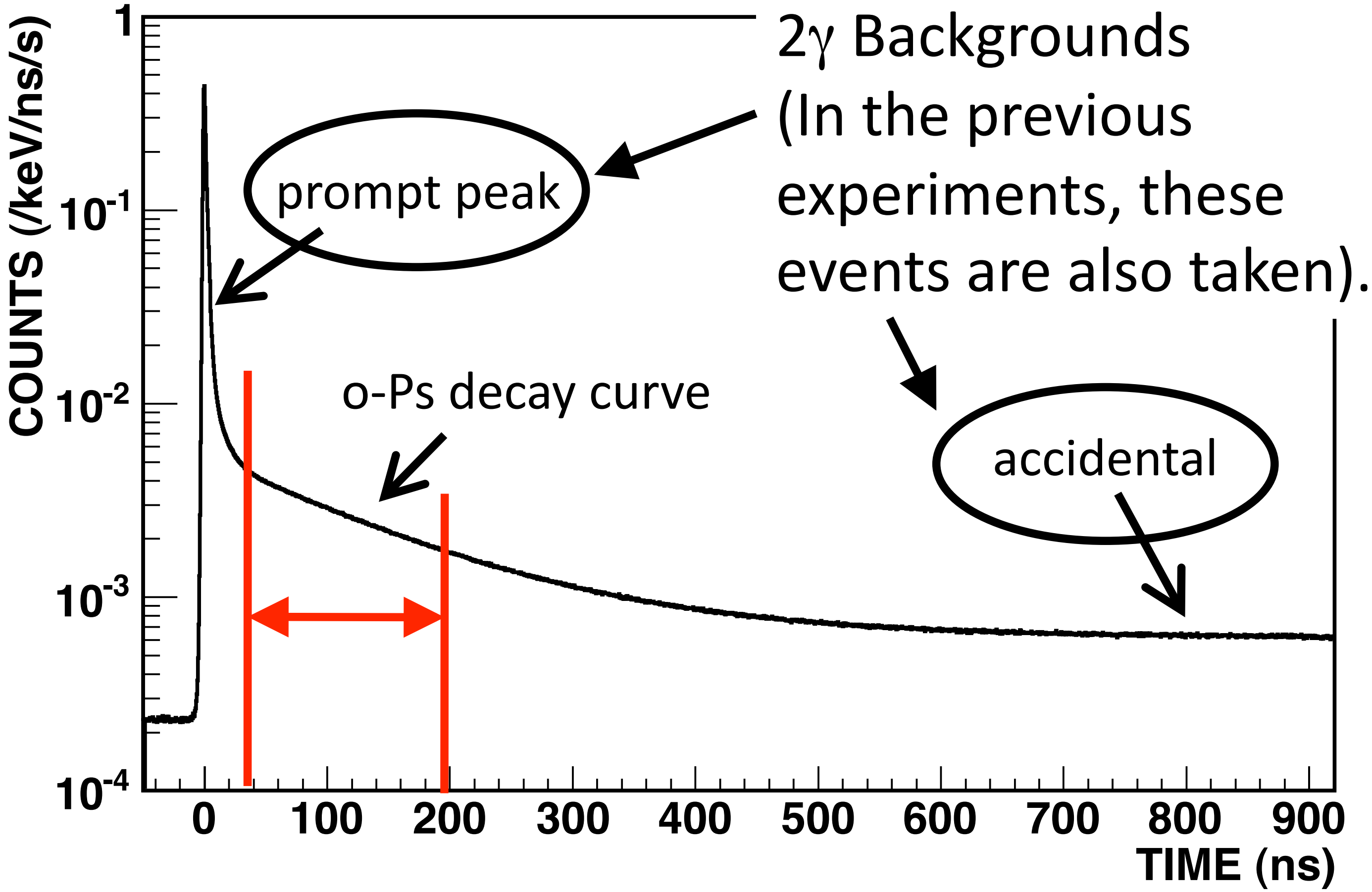
(2) Directly measure the Ps thermalization effect



Prompt Suppression

High S/N

Decay curve of Ps

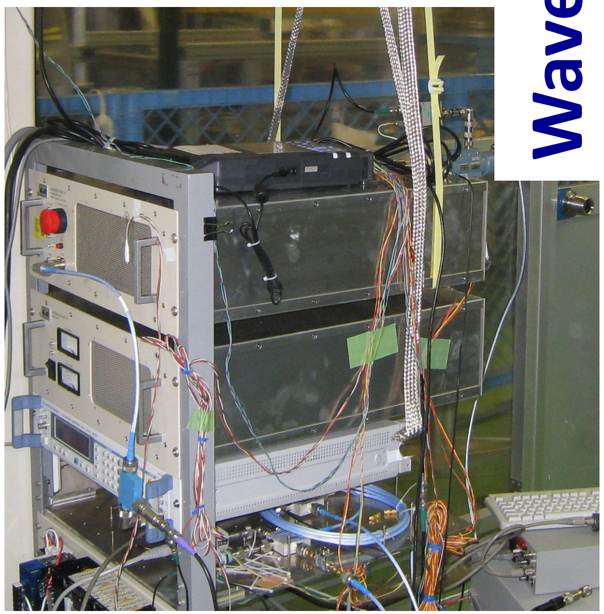


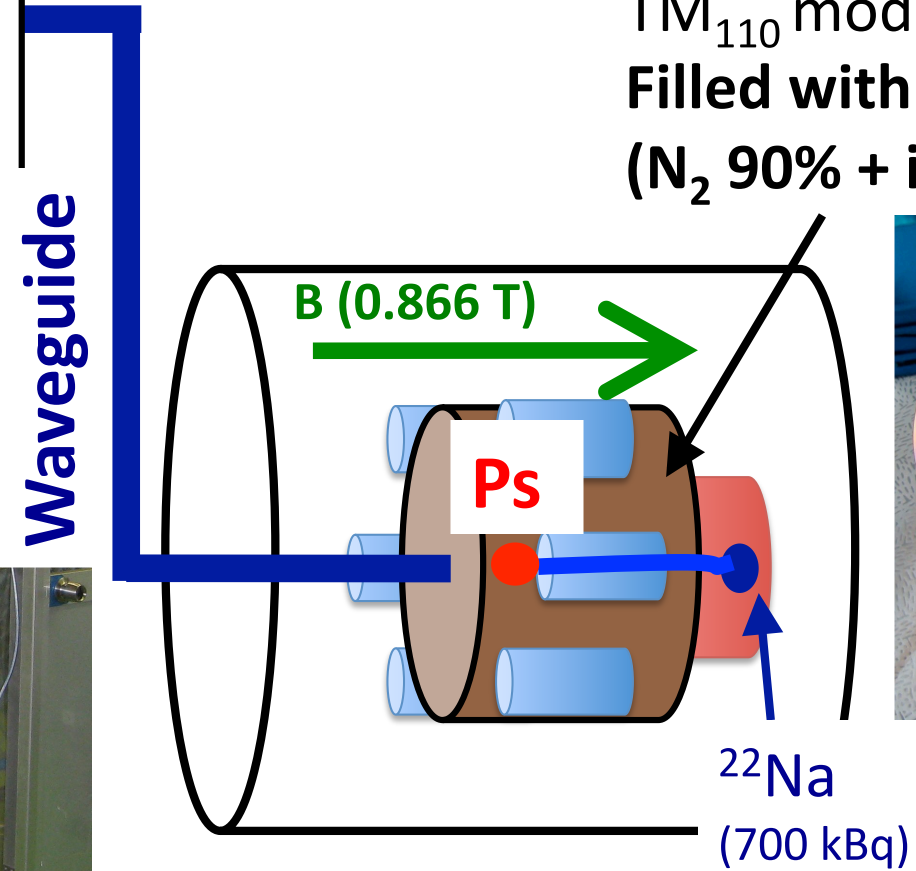
Select the o-Ps events (and Zeeman transition events) with
Timing window → About 20 times higher S/N

Our New Experiment

To reduce the systematic uncertainties, we use the following new methods.

RF SG +
GaN Amp.
2.9 GHz
500 W CW



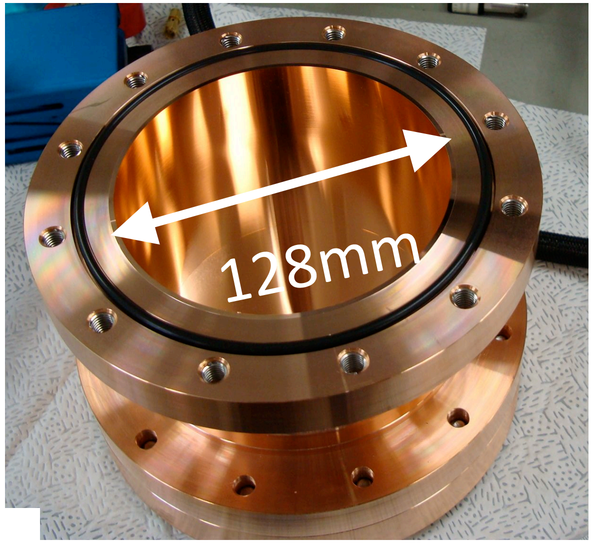


RF Cavity

TM_{110} mode, Q_L=14,700

Filled with gas

(N_2 90% + iso-C_4H_{10} 10%)

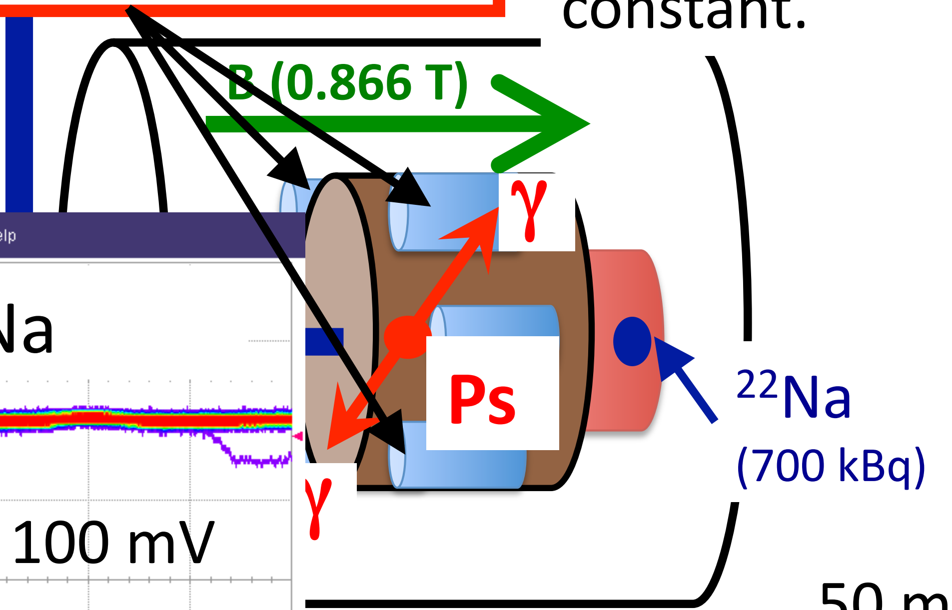


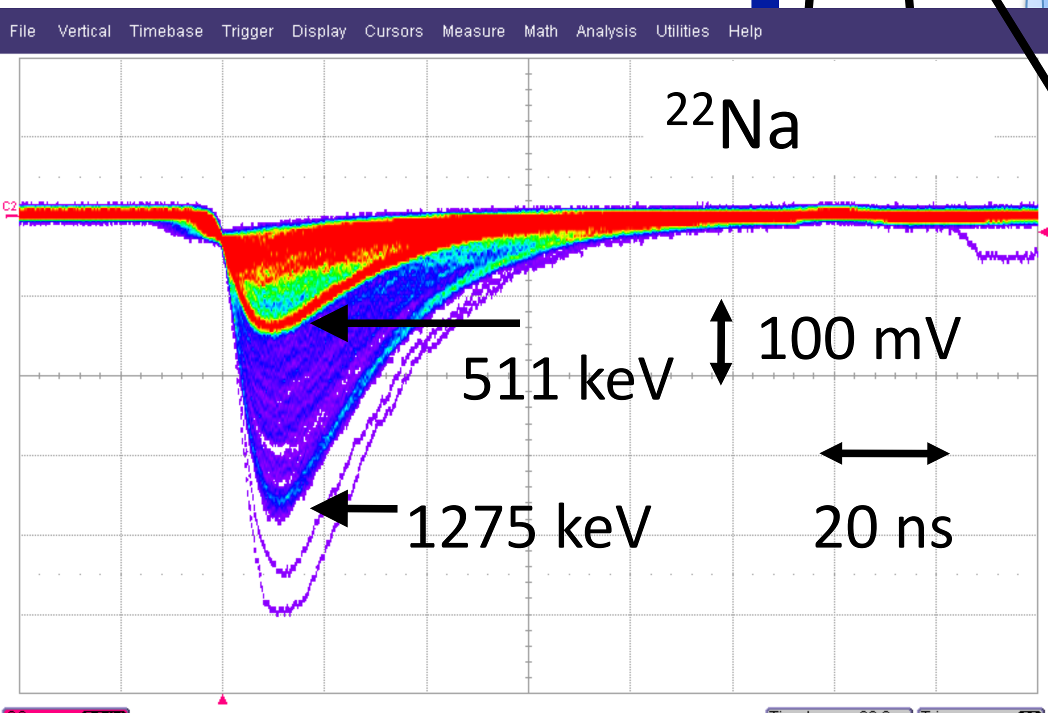
Our New Experiment

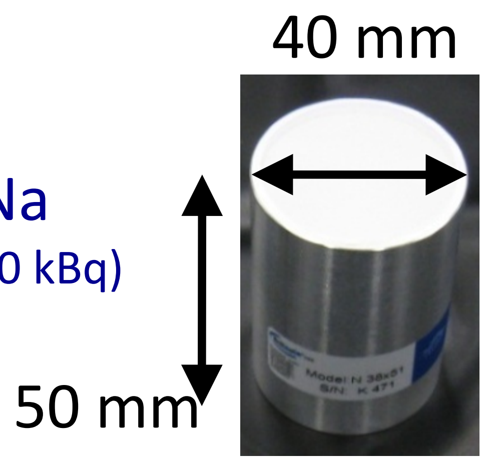
To reduce the systematic uncertainties, we use the following new methods.

·High performance (fast and high energy resolution) γ-ray detectors

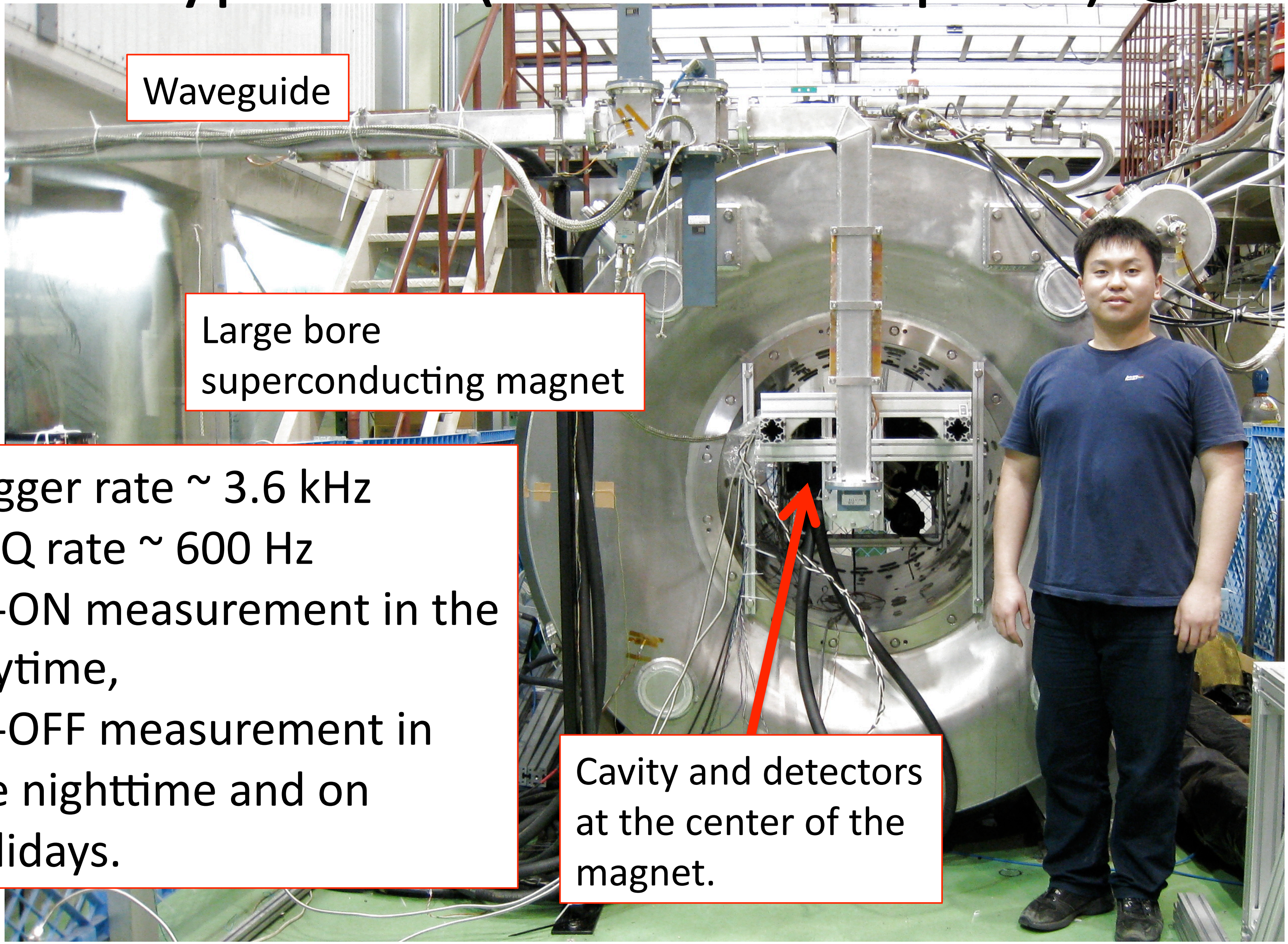
-**$LaBr_3$(Ce) scintillators** x 6
-**High energy (4%) and timing (200 ps) resolutions**, short (16 ns) decay constant.





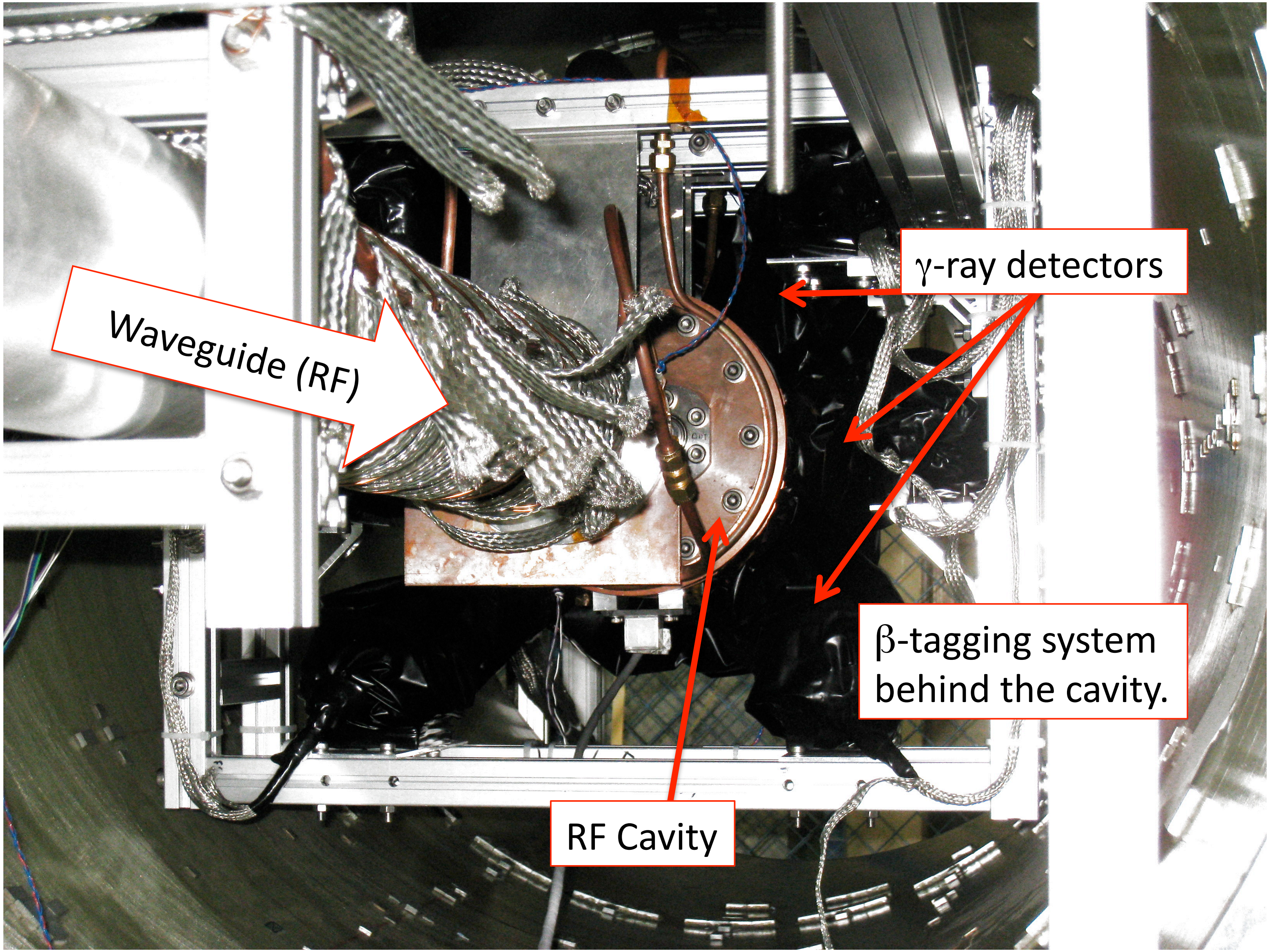


Our Experimental Setup
Prototype Run (2 Jul – 24 Sep ’09) @KEK



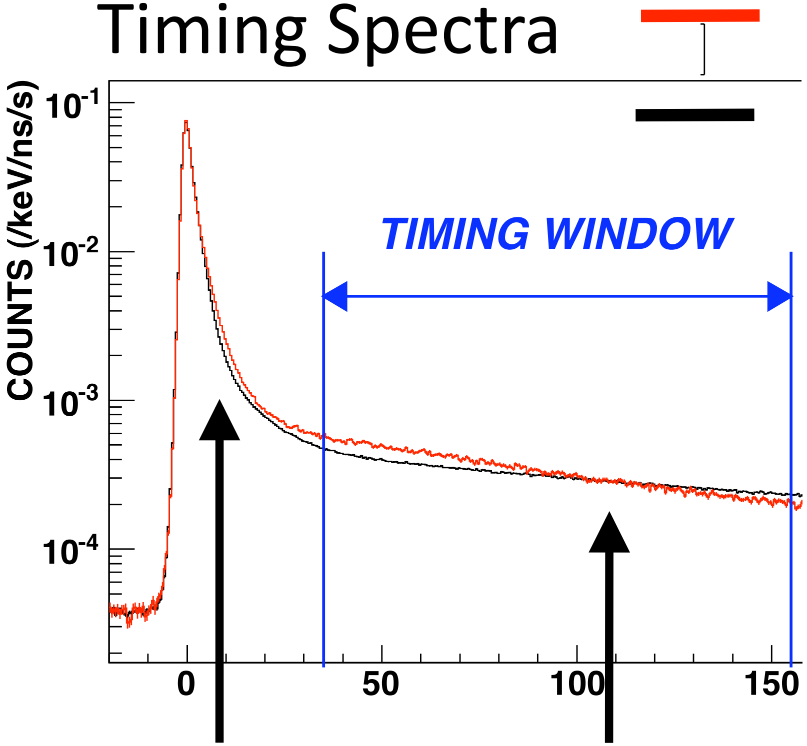
Trigger rate ~ 3.6 kHz
DAQ rate ~ 600 Hz
RF-ON measurement in the daytime,
RF-OFF measurement in the nighttime and on holidays.

Center of the Magnet



Analysis

Timing Spectra

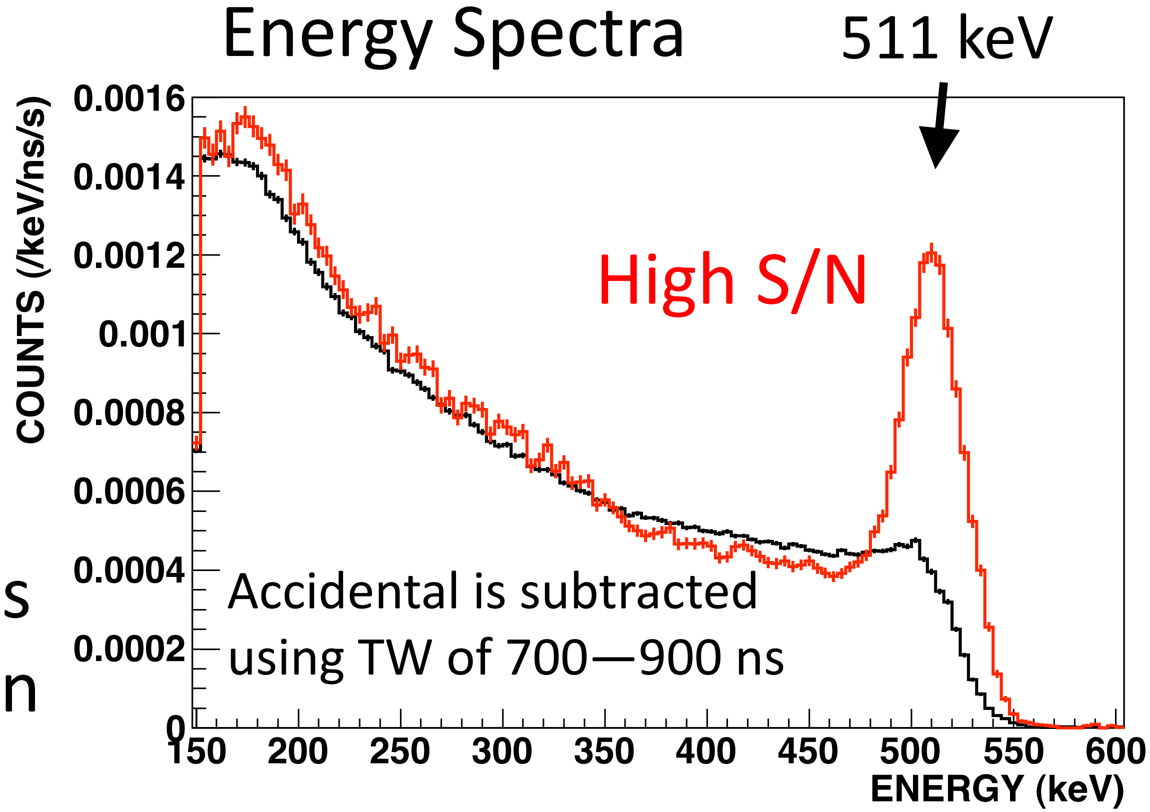


Short Component ($m_z = 0$)

Long Component ($m_z = \pm 1$)

Suppress Prompt and Accidental backgrounds with a Timing window of 35 ns – 155 ns

Energy Spectra



2γ decay rate increases because of the Zeeman transition.

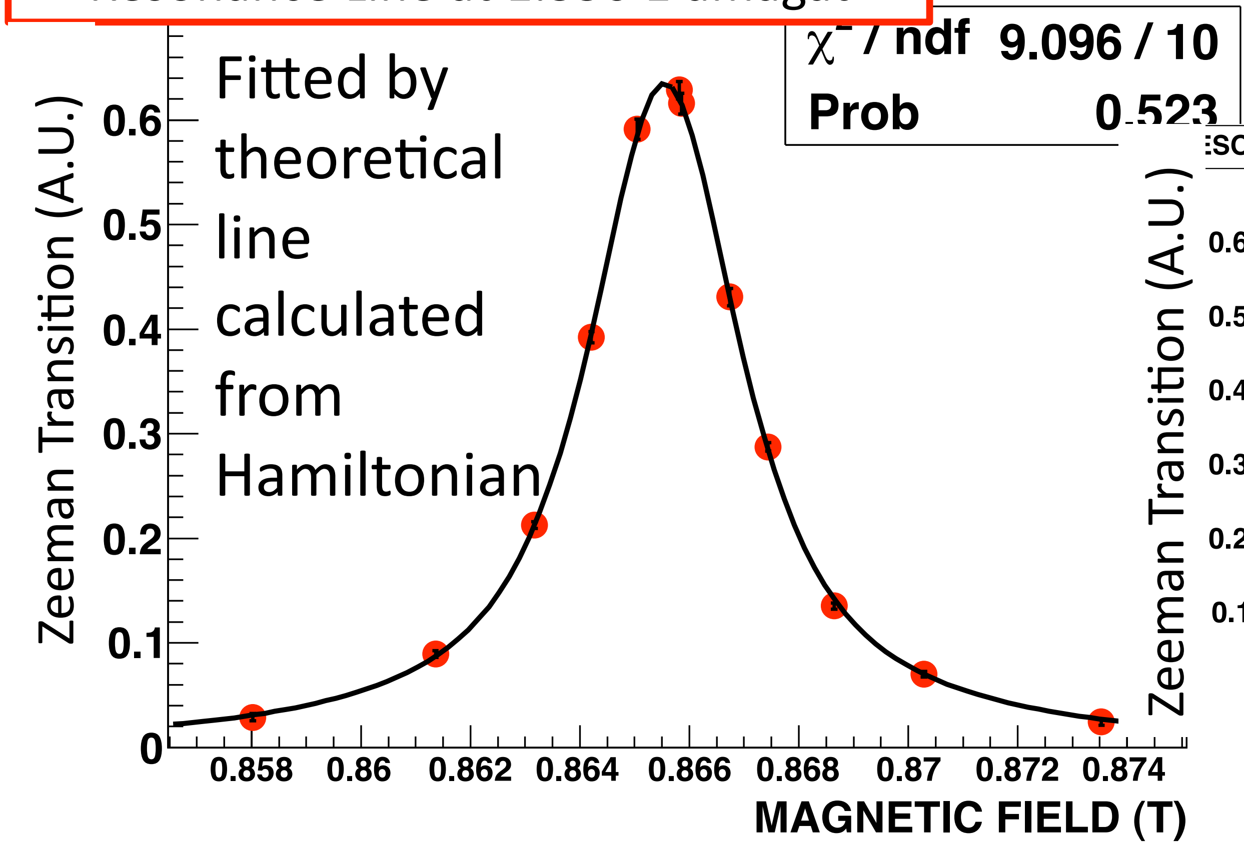
Resonance Lines

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

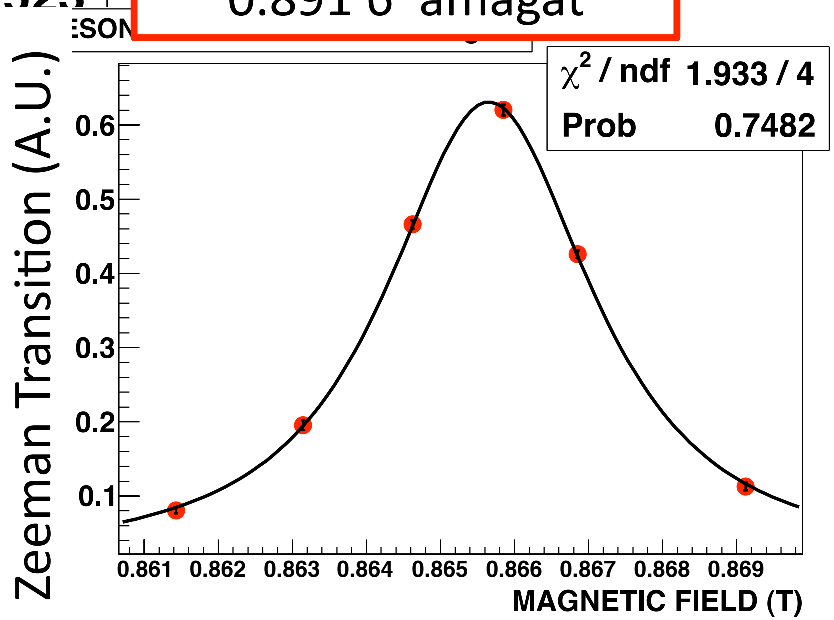
$2\gamma/3\gamma$ decay ratio is taken to be a Zeeman transition amount.

Resonance Line at 1.350 1 amagat

Fitted by theoretical line calculated from Hamiltonian



Resonance Line at 0.891 6 amagat

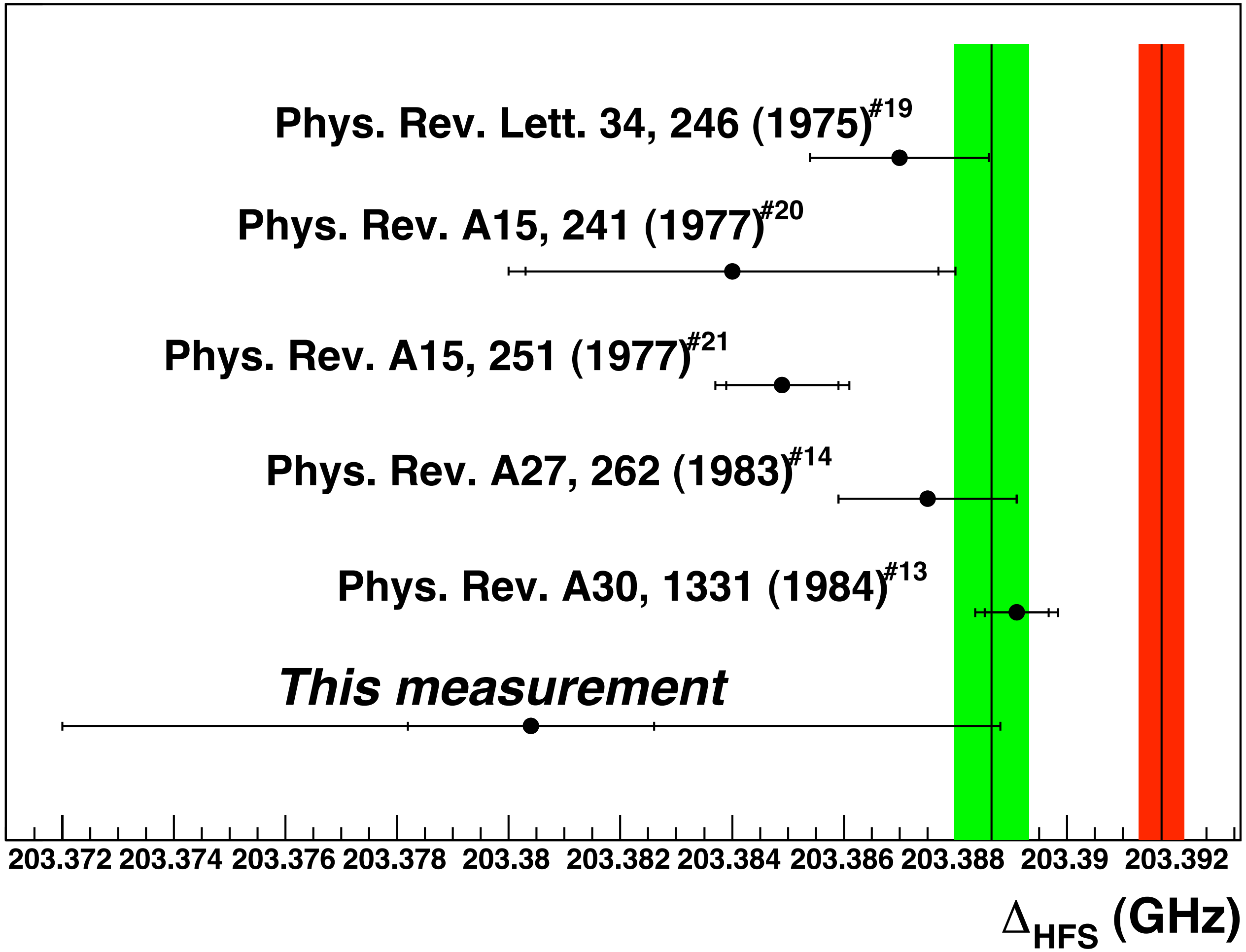


Δ_{HFS} = 203.368 3(55) GHz (27 ppm)

Δ_{HFS} = 203.379 3(70) GHz (34 ppm)

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

Result of the prototype run



- Our system has worked well.
- The result of the prototype run is consistent with the previous experiments and the theory.

Ps-HFS obtained from the Prototype Run:

$$\Delta_{HFS} = 203.380\,4 \pm 0.002\,2 \text{ (stat., 11 ppm)} \pm 0.008\,1 \text{ (sys., 40 ppm) GHz}$$

Systematic Errors

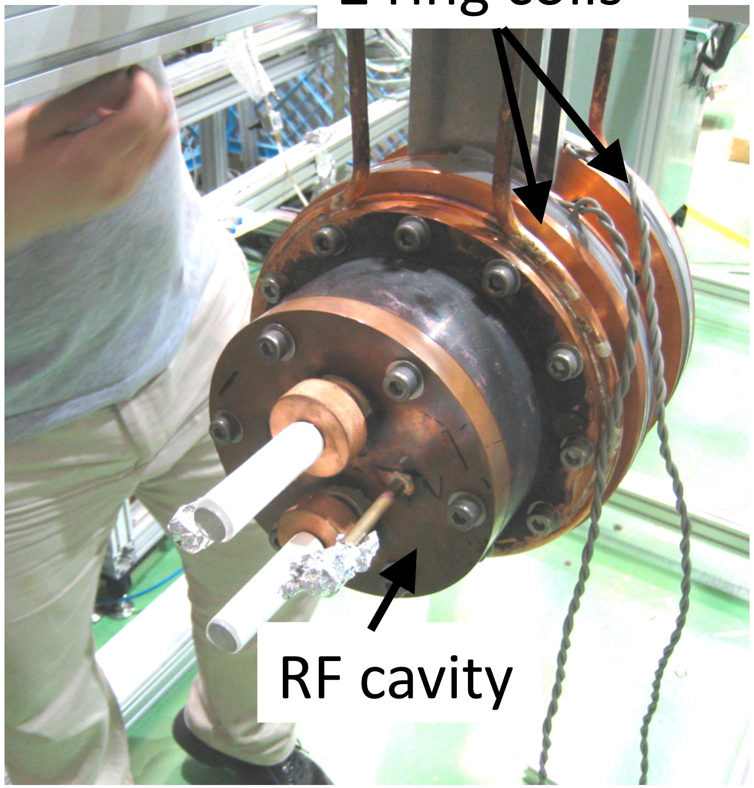
	Source	ppm in Δ_{HFS}
Magnetic Field	Non-uniformity	21
	Offset and reproducibility	4
	NMR measurement	2
Detection Efficiency estimation	Method	18
	Statistics of MC simulation	17
RF System	Q_L value of RF cavity	6
	RF power	5
	RF frequency	5
Material Effect	Thermalization of Ps	<20
	Gas density dependence	7
	Quadrature sum	40

Prospects & Current status

- Magnetic Field: Compensation magnets
  → O(ppm) magnetic field uniformity (Done → Next page)
- Material Effect: Measurements at various pressures of gas → Estimate the Stark Effect (Final measurement)
  Precisely measure the Ps thermalization
  (Now taking data)
- RF System: The experimental environment (temperature) control → Almost cleared.
- Statistics: 85-day prototype run achieved 11 ppm. A measurement with a precision of O(ppm) is expected within a few years.
- Detection efficiency: Will be carefully studied and will be estimated by real data.

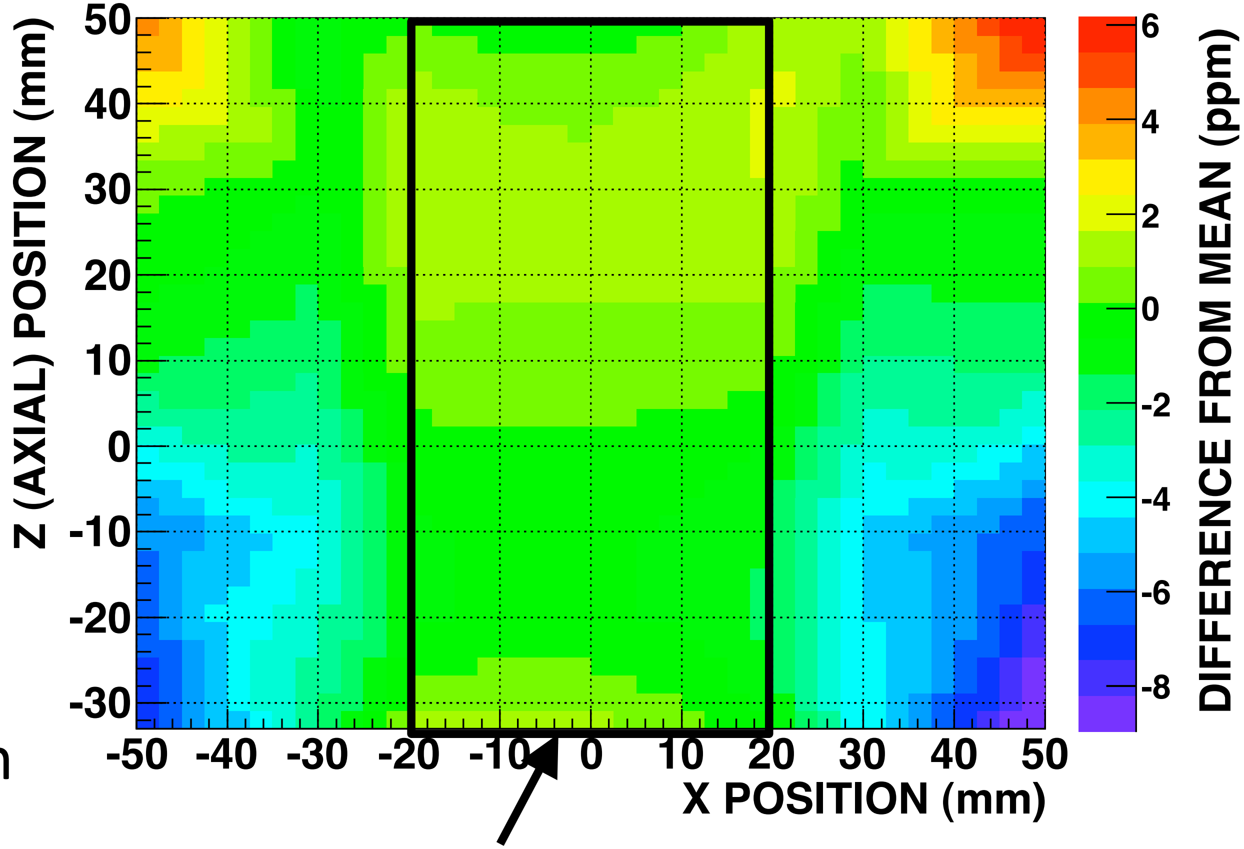
→ O(ppm) systematic error. (Not yet)

Compensation Magnet



- 2 ring-coils are rolled on the cavity flange.
- They make the opposite field and reduce the gradient.

Magnetic Field distribution (Horizontal)
(O is the center of the cavity)



0.9 ppm (RMS) uniformity in the Ps formation volume (10.4 ppm w/o coils)

→ It is installed in the final run setup.

Conclusion

- There is a 3.9 σ discrepancy in the ground state Ps-HFS between the experimental results and the QED prediction.
- We propose a new experiment to measure the Ps-HFS with timing information.
- Our experiment reduces possible common uncertainties in previous experiments (Non-uniformity of magnetic field, Ps thermalization effect).
- The prototype run has been performed.
- The preliminary value of Ps-HFS with an accuracy of 41 ppm has been obtained from the prototype run.
- A new result with an accuracy of O(ppm) will be obtained within a few years which will be an independent check of the discrepancy.