First Spectroscopy of the Hyperfine Interval of Positronium Using Millimeter Waves

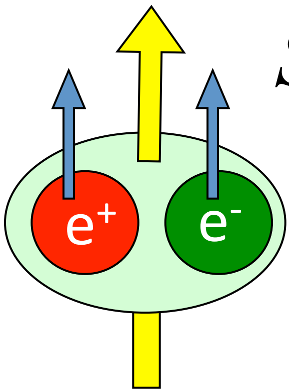
Akira Miyazaki (The University of Tokyo→CERN)

T. Yamazaki, T. Suehara, T. Namba
S. Asai, T. Kobayashi, H. Saito
(The University of Tokyo)

Y. Tatematsu, I. Ogawa, T. Idehara
(Fukui University)

INTRODUCTION

Spin Eigenstates of ground-state Posiotronium (Ps)



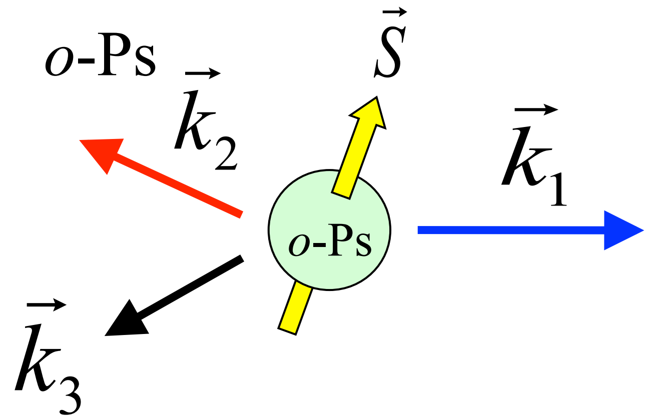
$\vec{S}$ = 1 (Triplet)

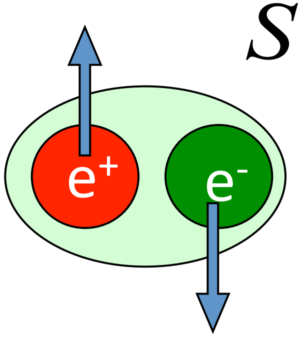
lifetime = 142 ns

ortho-positronium (o-Ps)

three photon decay

$o\text{-Ps} \rightarrow 3\gamma$ (, 5γ, ...)





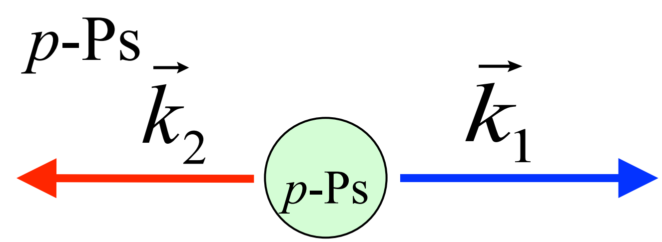
$\vec{S}$ = 0 (Singlet)

lifetime = 125 ps

para-positronium (p-Ps)

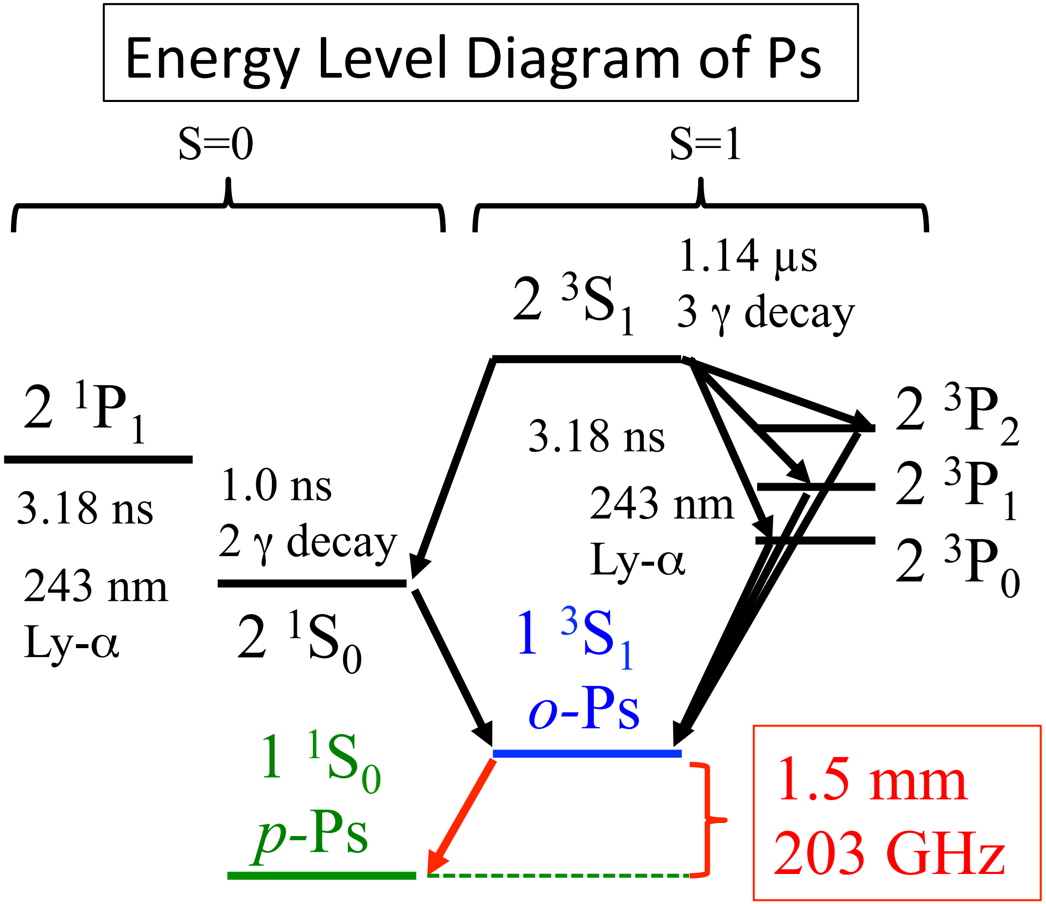
two photon decay

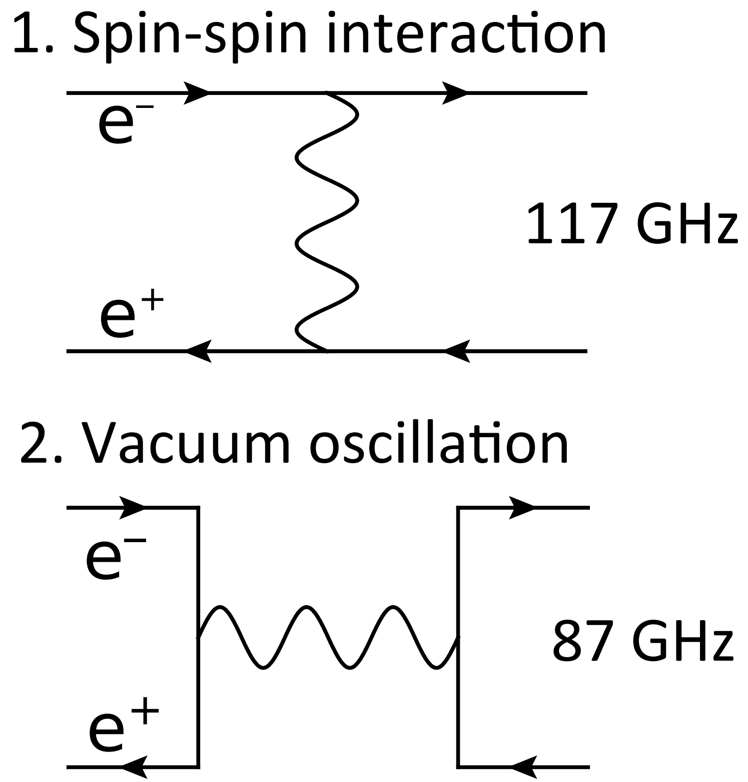
$p\text{-Ps} \rightarrow 2\gamma$ (, 4γ, ...)



back-to-back 511 keV

Hyperfine structure of Ps (Δ_{HFS})





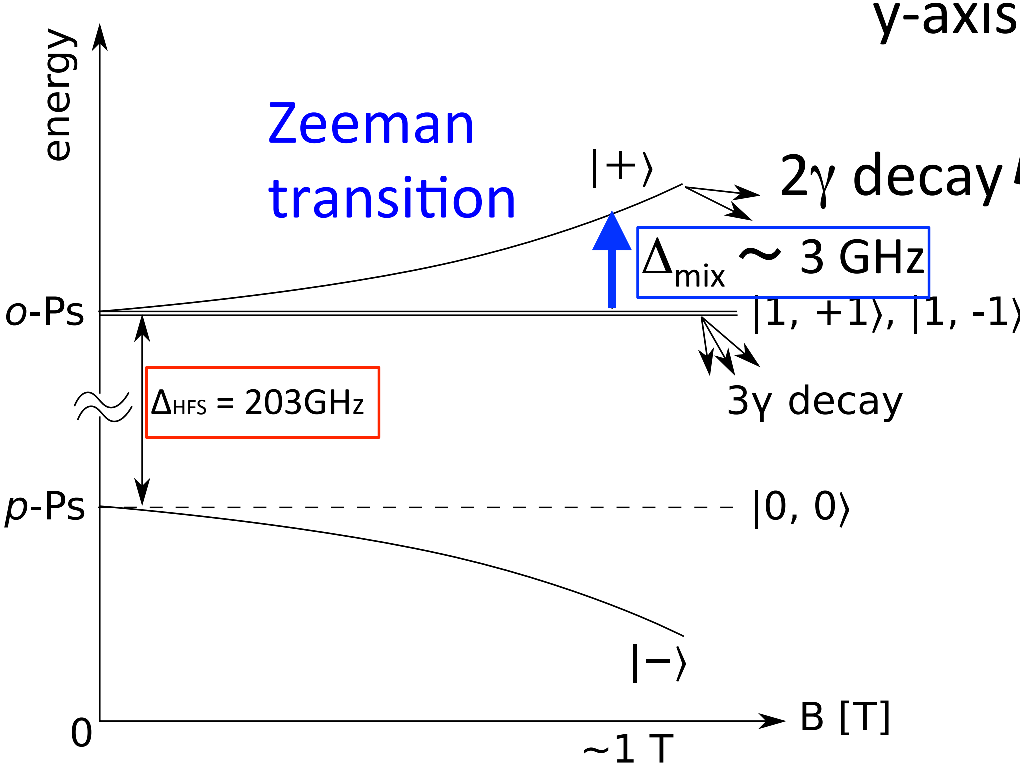
The spin-spin interaction and vacuum oscillation raises *o*-Ps energy from *p*-Ps one by Δ_{HFS} = 203 GHz (>>hydrogen's HFS 1.4GHz)

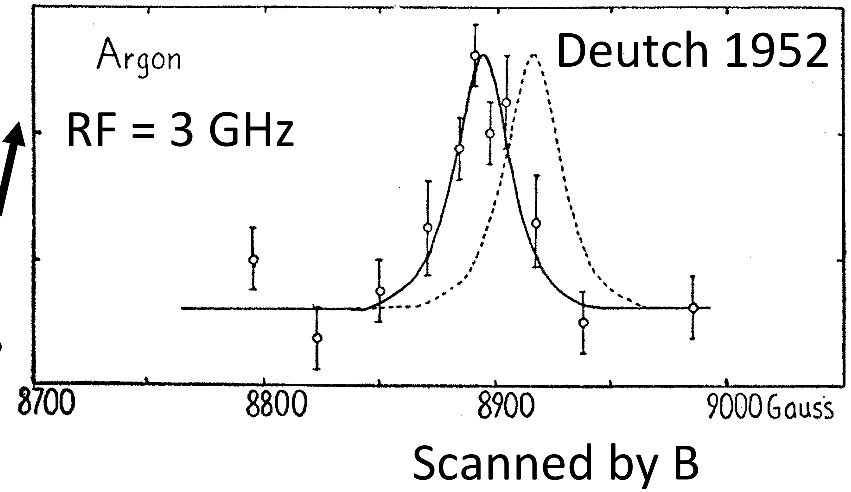
No established method to treat millimeter waves

→ How was Δ_{HFS} determined so far?

Solution in literature

Measure the Zeeman shifted levels → Δ_{HFS} was then calculated



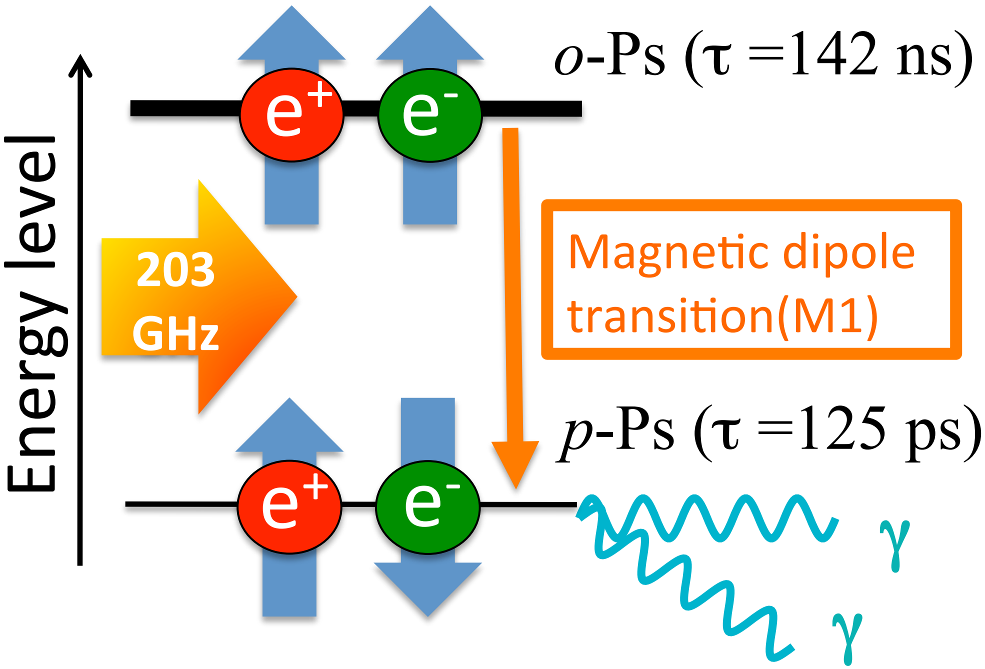


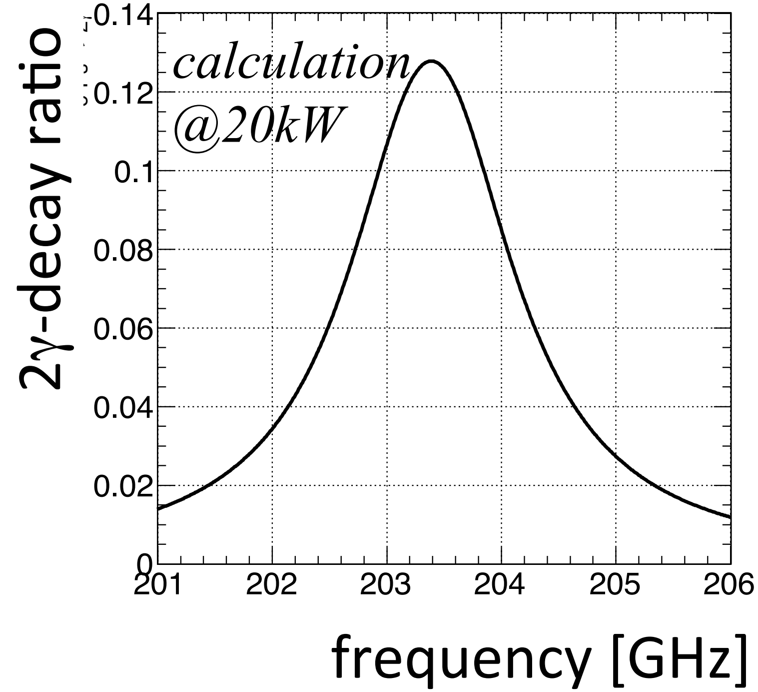
$$\begin{cases} \Delta_{\rm mix} = \dfrac{\Delta_{\rm HFS}}{2}\left(\sqrt{1+x^2}-1\right) \\ x = \dfrac{2g'\mu_B B}{h\Delta_{\rm HFS}} \end{cases}$$

$g' = g(1 - 5/24\alpha^2)$

In such a way, Δ_{HFS} is determined with accuracy of about a few ppm.
However, Δ_{HFS} is originally derived in a fundamental way for free Ps
→ Can we directly measure Δ_{HFS} with leading-edge technology today?

Simple method, but…





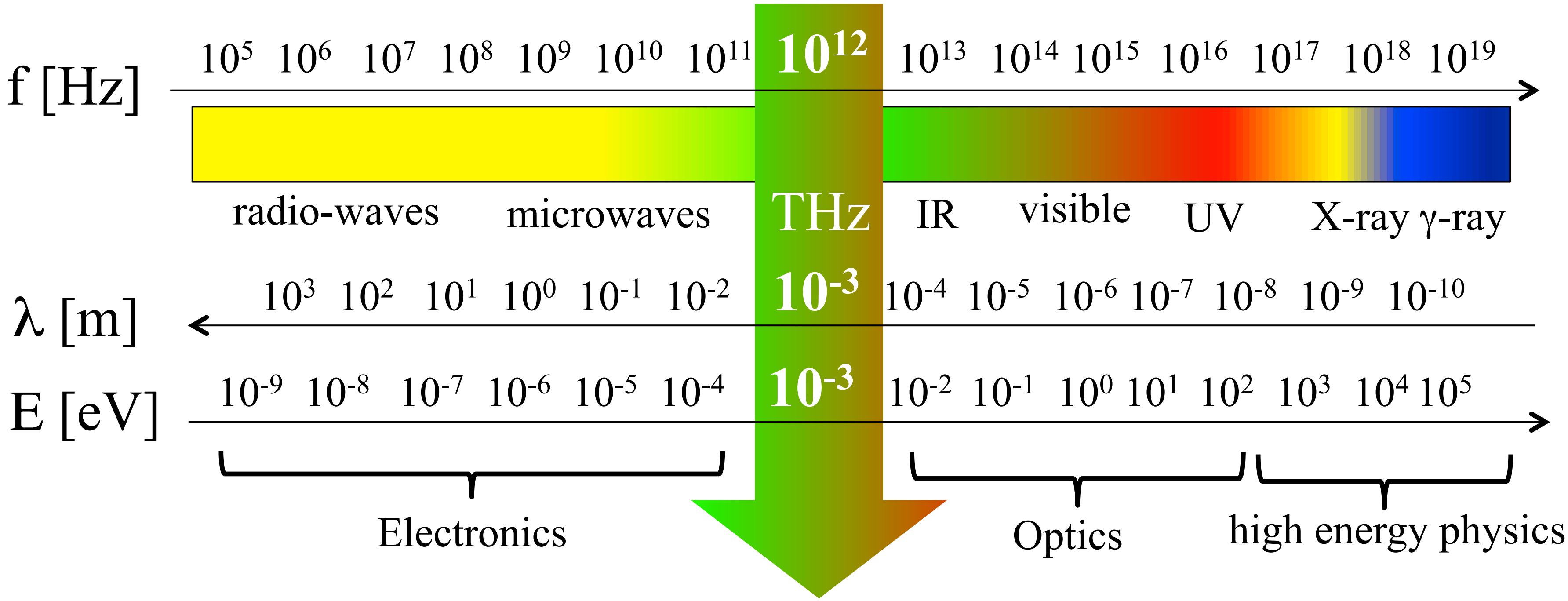
- 203GHz radiation induces the transition from *o*-Ps to *p*-Ps (M1)
- The transiting *p*-Ps decays into 2 γ rays (511 keV) in 125 ps

→The 2γ-decay ratio becomes the Breit-Wigner curve (mean = Δ_{HFS})

- High power of over 10 kW is required because of short lifetime of Ps
- Frequency should be scanned from 201 GHz to 206 GHz

→ Are they difficult to achieve today??

Yes! Millimeter waves are still very difficult



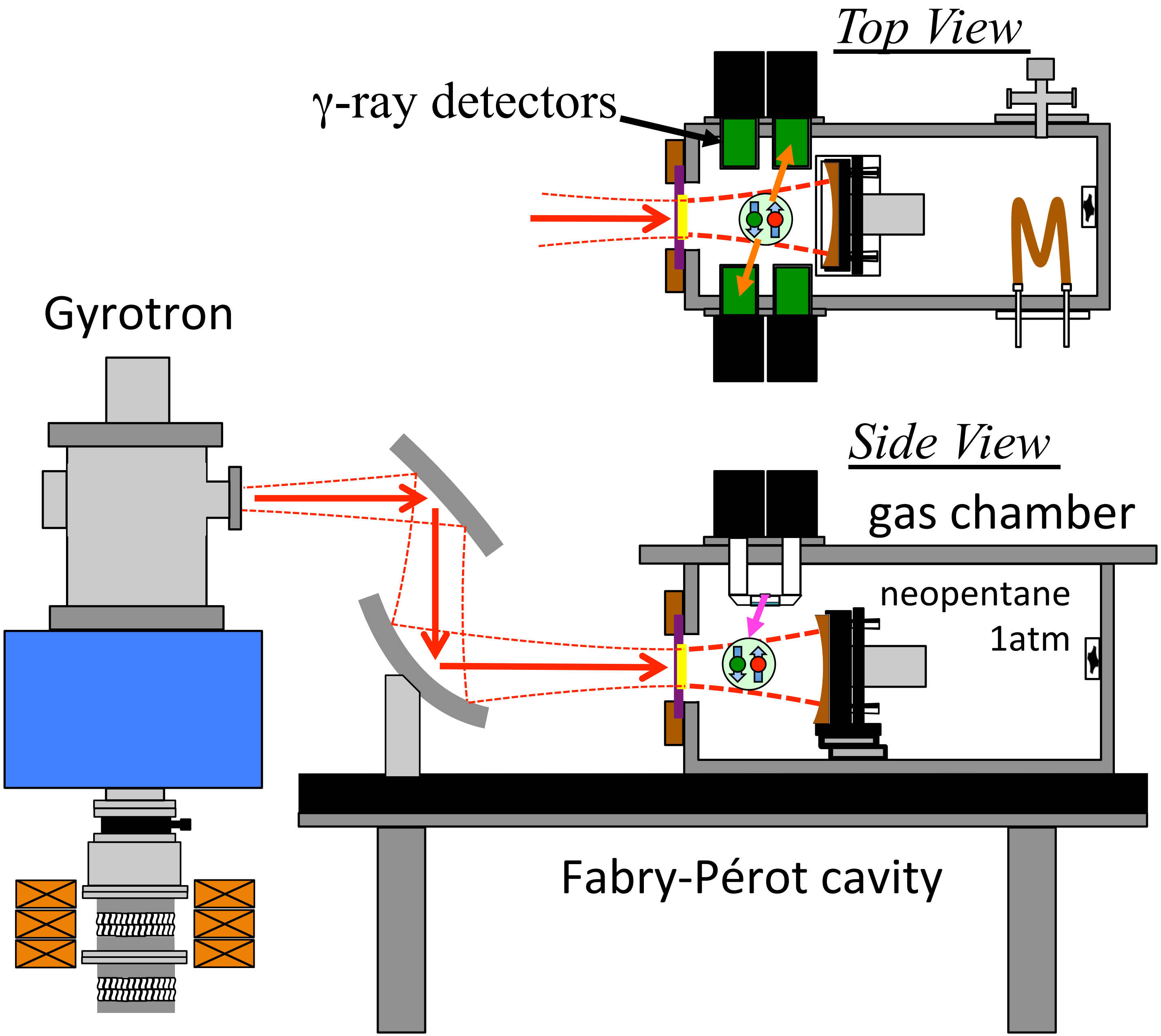
THz Gap = millimeter wave

☆High-power millimeter-wave spectroscopy is quite unique

Newly developed two devices:

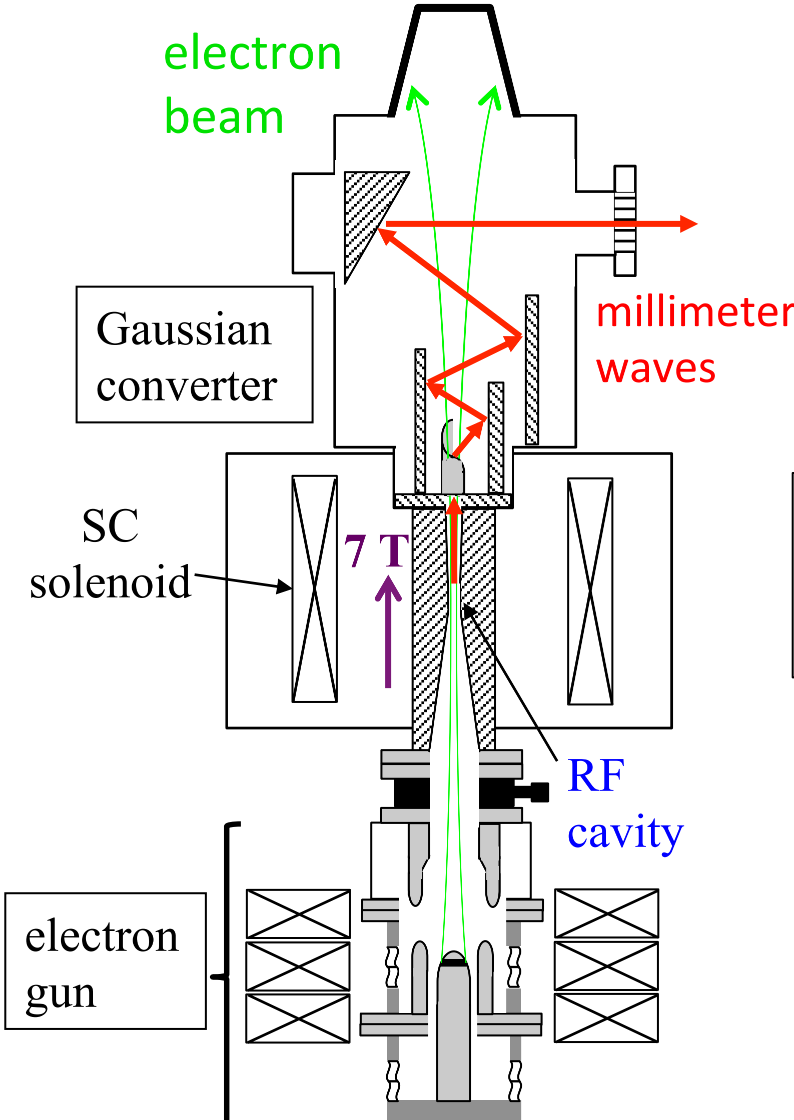
1. A millimeter-wave oscillator of over 100 W (Gyrotron)
2. A resonant cavity accumulating over 20 kW (Fabry-Pérot cavity)

Experimental setup



MILLIMETER-WAVE DEVICES

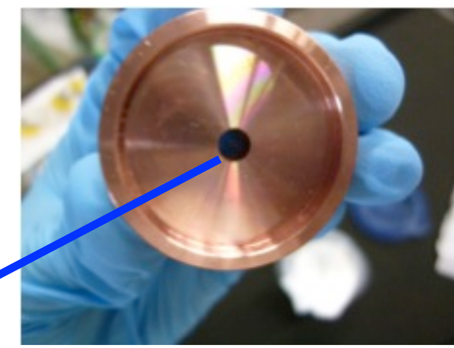
Gyrotron oscillator



A gyrotron is a high-power CW oscillator of millimeter waves.

The electrons thermally emitted from the gun move in a cyclotron motion in a magnetic field

$$\omega_c = \frac{eB}{m_e \gamma} \sim 200\ \mathrm{GHz}$$

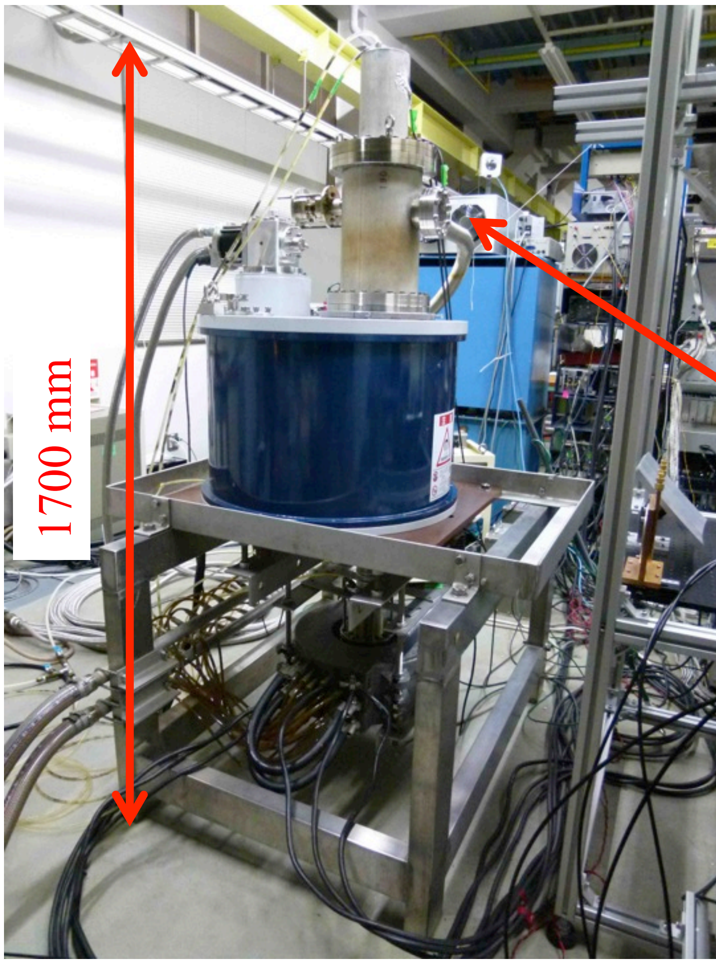


In the RF cavity (an open-ended cavity of ϕ5mm), electron beam couples and excites a TE modes ($\sim \omega_c$)

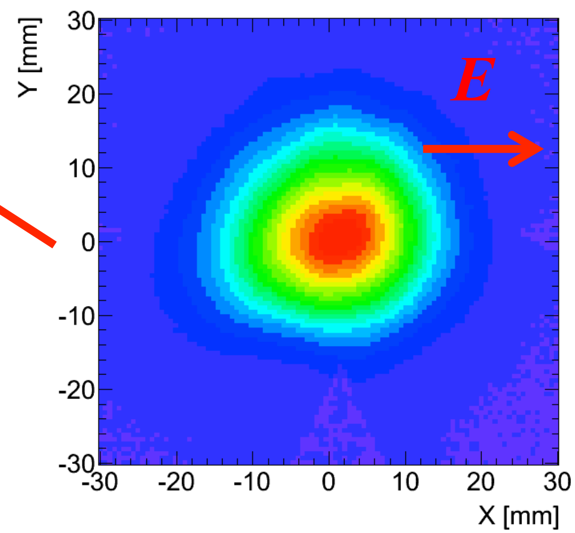
→ cyclotron-maser resonance

Developed gyrotron

collaboration with Fukui University



Power = 100 – 600 W



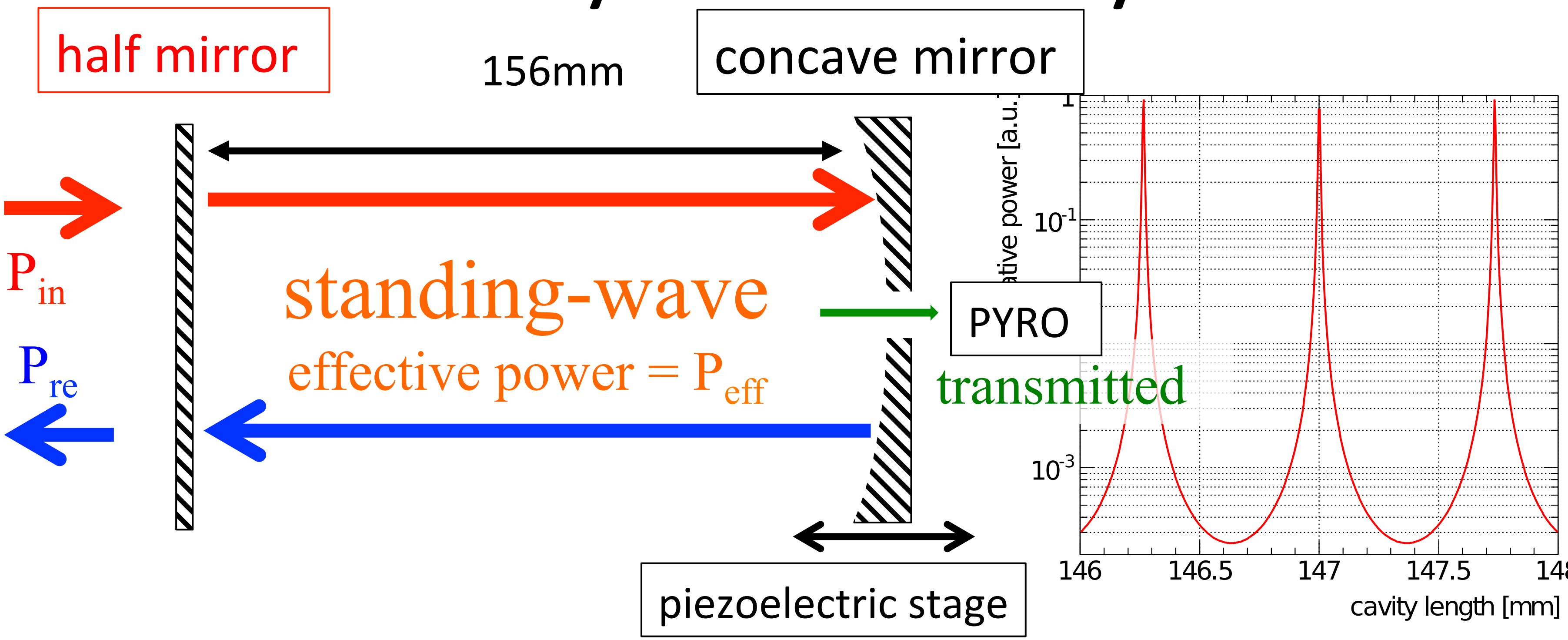
Output radiation is converted from a TE_{52} mode to TEM_{00} using geometrical optics

Output power is limited by the power supply (CW, 18kV, 500 mA)

→A resonant cavity is required.

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

Fabry-Pérot cavity



•A Fabry-Pérot cavity resonates when cavity length matches λ/2 x p

•The resonance is monitored by a pyroelectric detector (PYRO) through a small hole (ϕ0.6 mm) on a copper concave mirror.

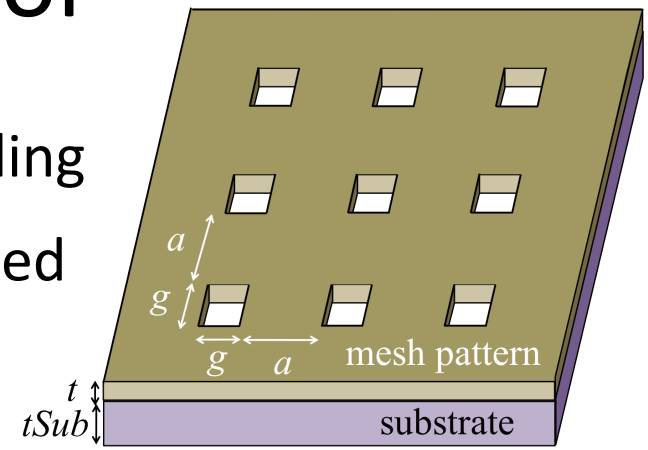
•The cavity length is controlled (<1μm) with a piezoelectric stage

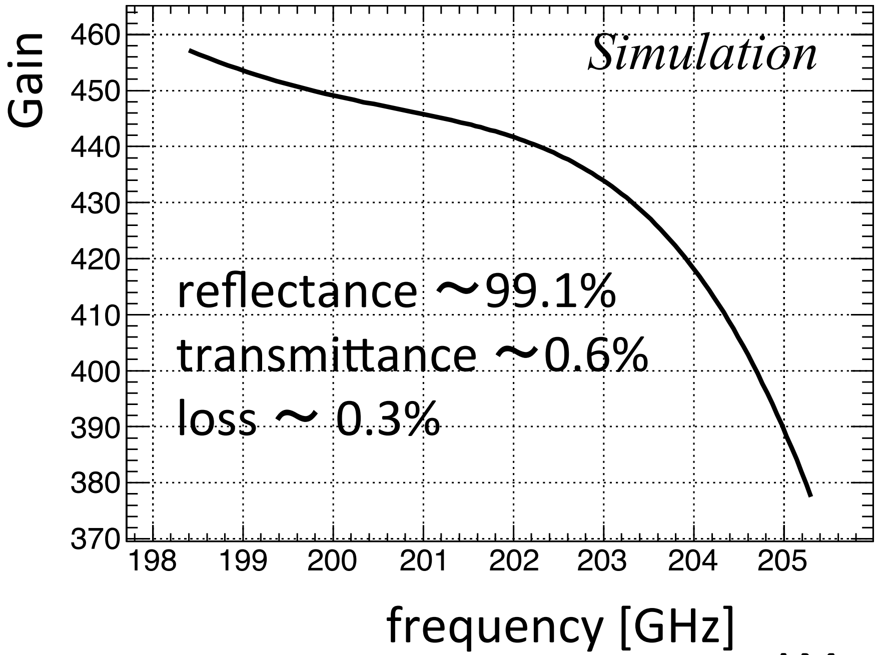
☆High-reflectance and low-loss half mirror are required for high-Q

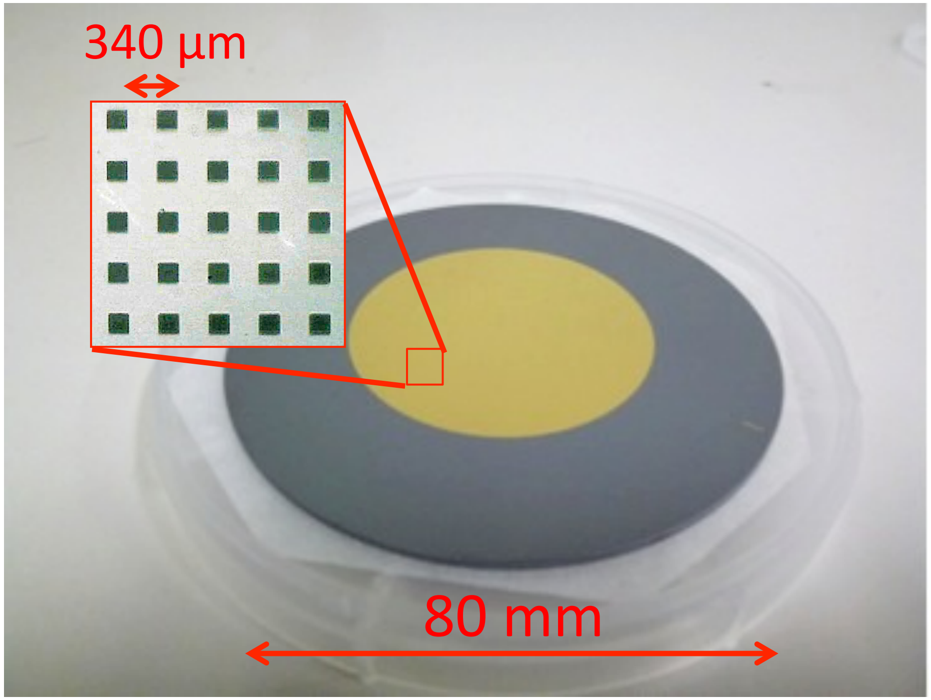
→ I designed a gold mesh mirror as an efficient half mirror!

Gold mesh mirror

- Thin (1μm) gold film is evaporated on a high-resistive silicon base (1.96mm) with water-cooling
- Using CST MW Studio, gain (P_{eff}/P_{in}) is optimized to have small frequency dependence (<10%) (a=200μm, g=140μm)



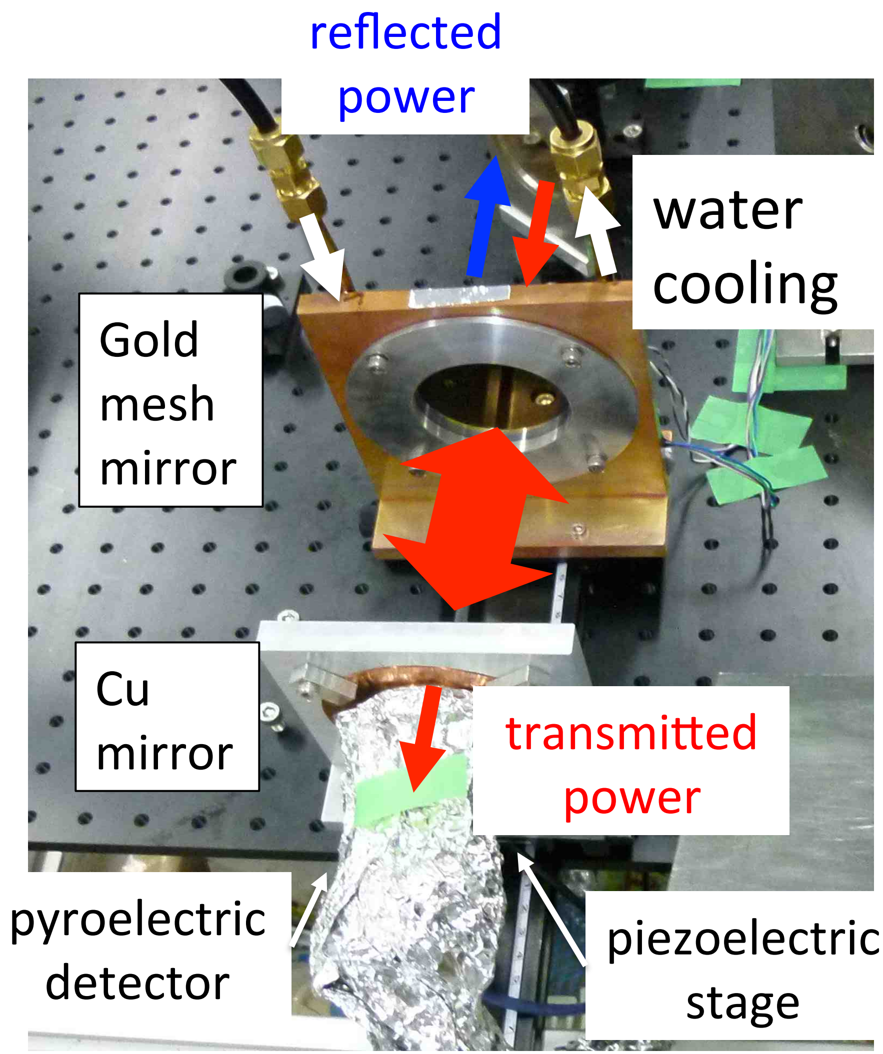


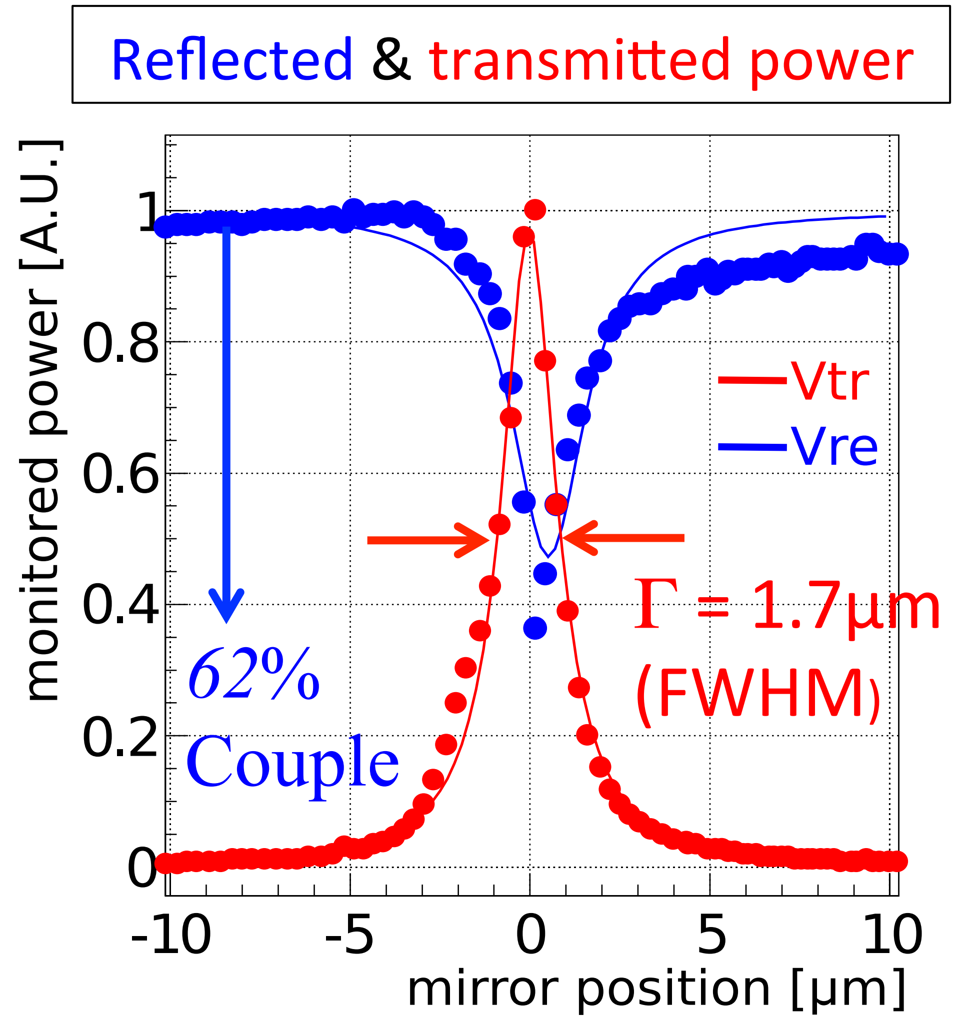


AM, et al., J. Infrared Milli. Terahz Waves 35, 1, 91 (2014)

Designed gain 400 → 100W input means 40kW effective power

Test of the Fabry-Pérot cavity





Γ and Coupling → Obtained P_{eff} is inaccurate (ΔP_{eff}>>50%)

→A better calibration method (ΔP_{eff} ~ 20%) is required.

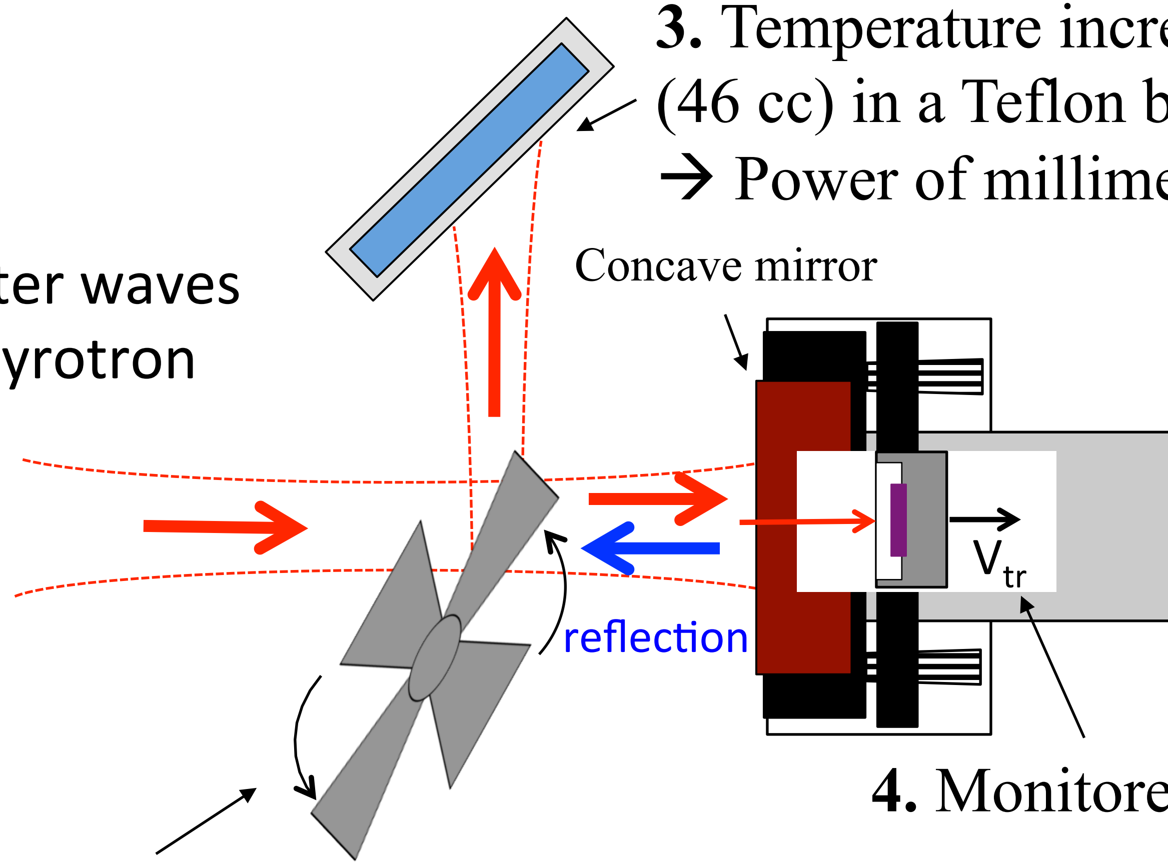
Estimation of P_{eff}

Transmitted power samples stored *effective* power

→calibration coefficient C (accuracy ~ 20%)

3. Temperature increase of water (46 cc) in a Teflon box
→ Power of millimeter waves P_{in}

1. Millimeter waves from the gyrotron



2. Divide the beam by a chopper (no frequency dependence)

4. Monitored voltage V_{tr}

$C = P_{in} / V_{tr}$ [kW/V]

→$P_{eff} = 2CV_{tr}$ [kW]

Experiments were done at eight different frequencies

The frequency is scanned by changing the RF cavity in the gyrotron.

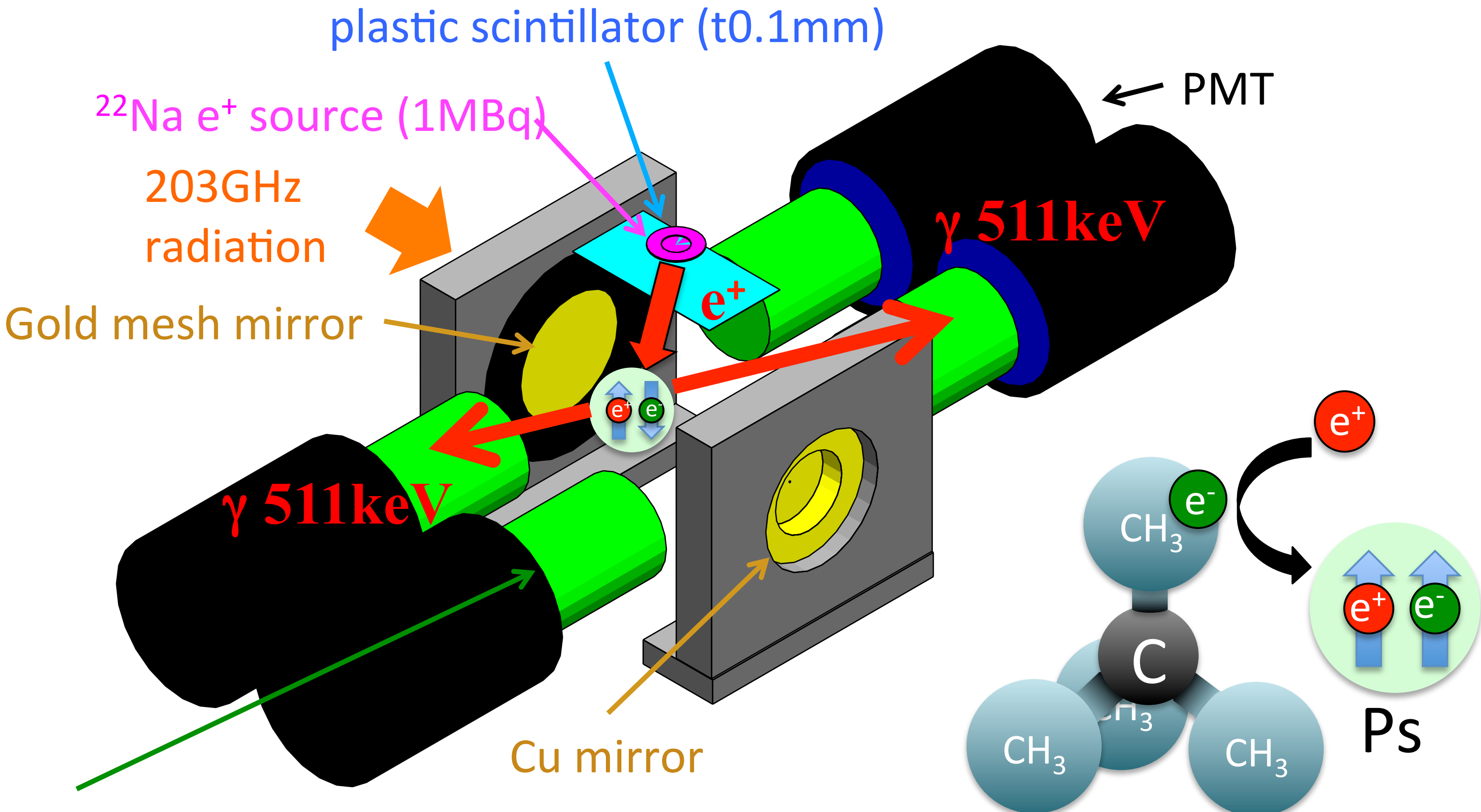
→ Frequency tuning is new in the high-power millimeter-wave range.

cavity radius	f	P_{eff}
(*)2.453 mm	180.59 GHz	41 kW
2.481 mm	201.83 GHz	22 kW
2.475 mm	202.64 GHz	23 kW
2.467 mm	203.00 GHz	21 kW
(**)2.467 mm	203.25 GHz	21 kW
2.463 mm	203.51 GHz	41 kW
2.453 mm	204.56 GHz	20 kW
2.443 mm	205.31 GHz	24 kW

(*) different resonant mode TE_{42} (**) Radius was expanded during the measurement

SETUP FOR PS PRODUCTION AND DETECTION

Ps production assembly & γ-ray detector



$LaBr_3(Ce)$ crystal scintillator

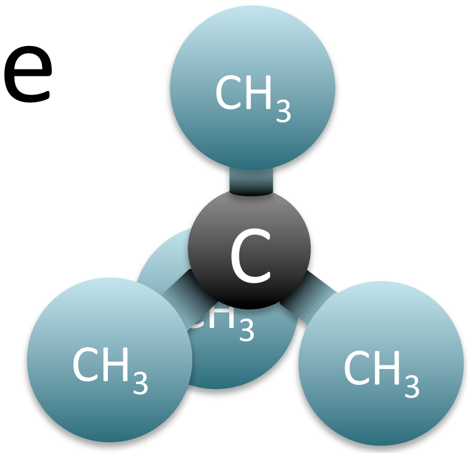
-High energy resolution (FWHM 4%@511keV)

-Small pileup (decay constant = 16ns)

-High stopping power

Ps is formed with e^+ from the source and e^- in a neopentane gas molecule

Gift from Neopentane

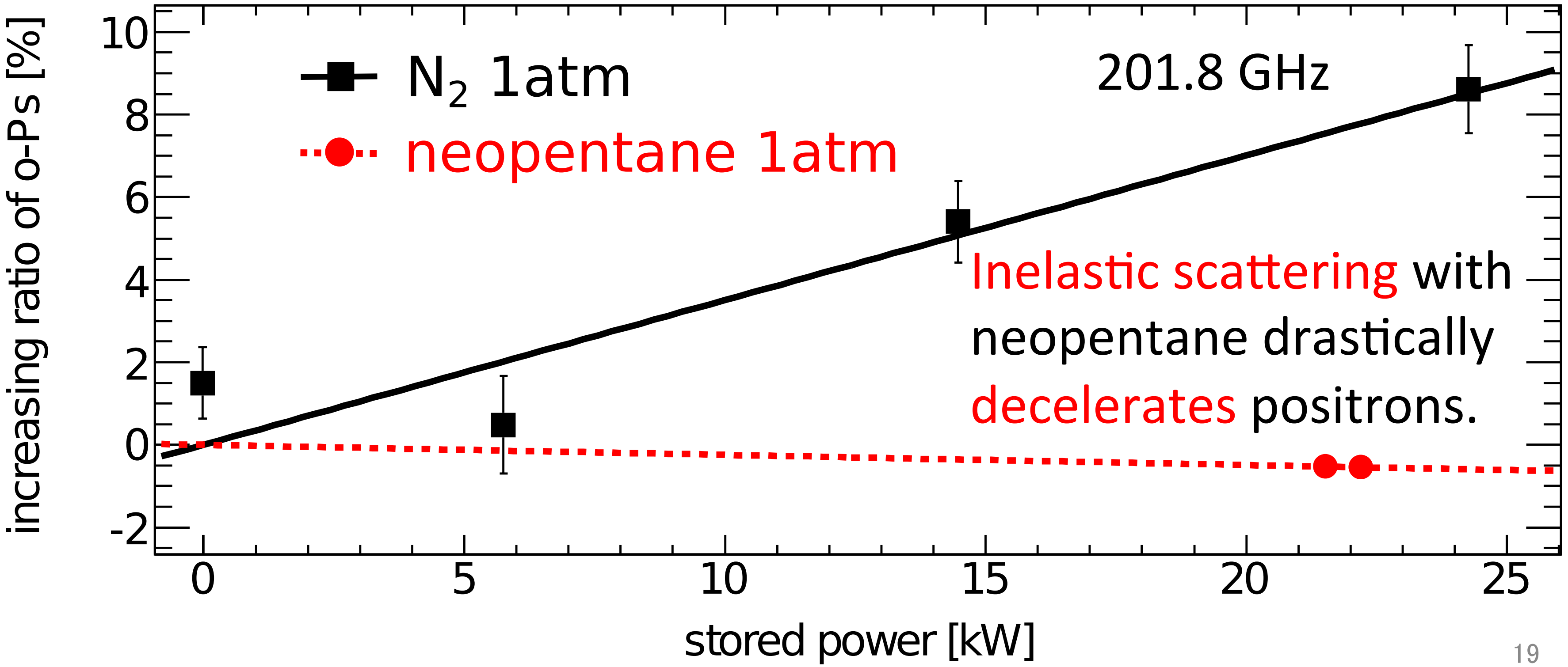


- Large background is found in N_2 gas
- Ps production ratio increases with stored power

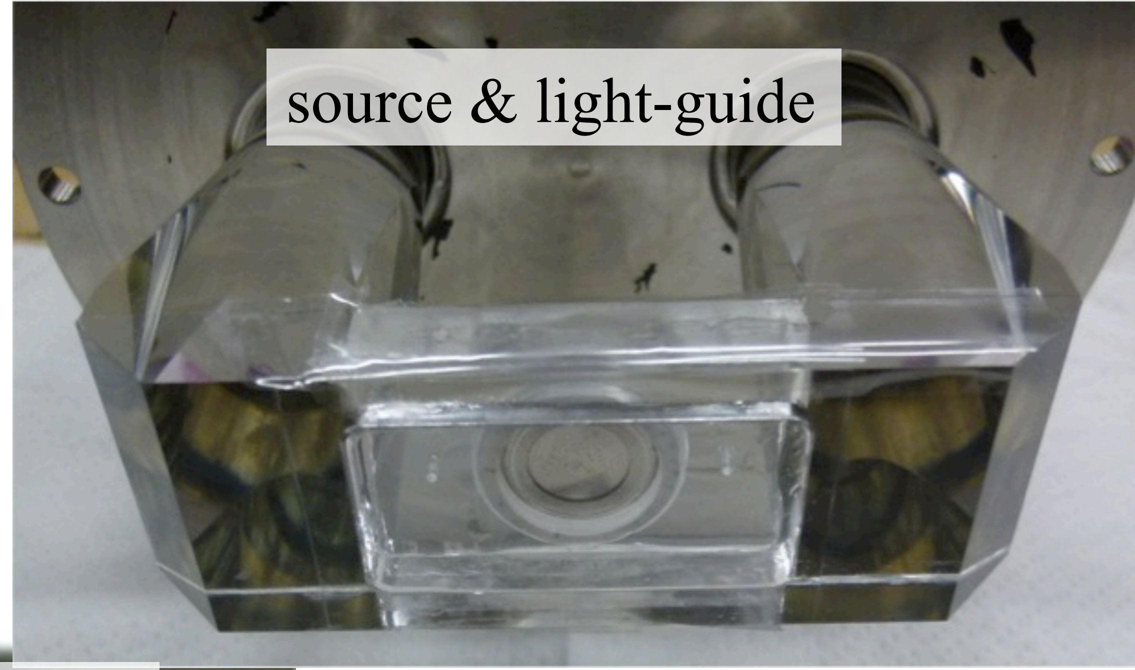
Reason

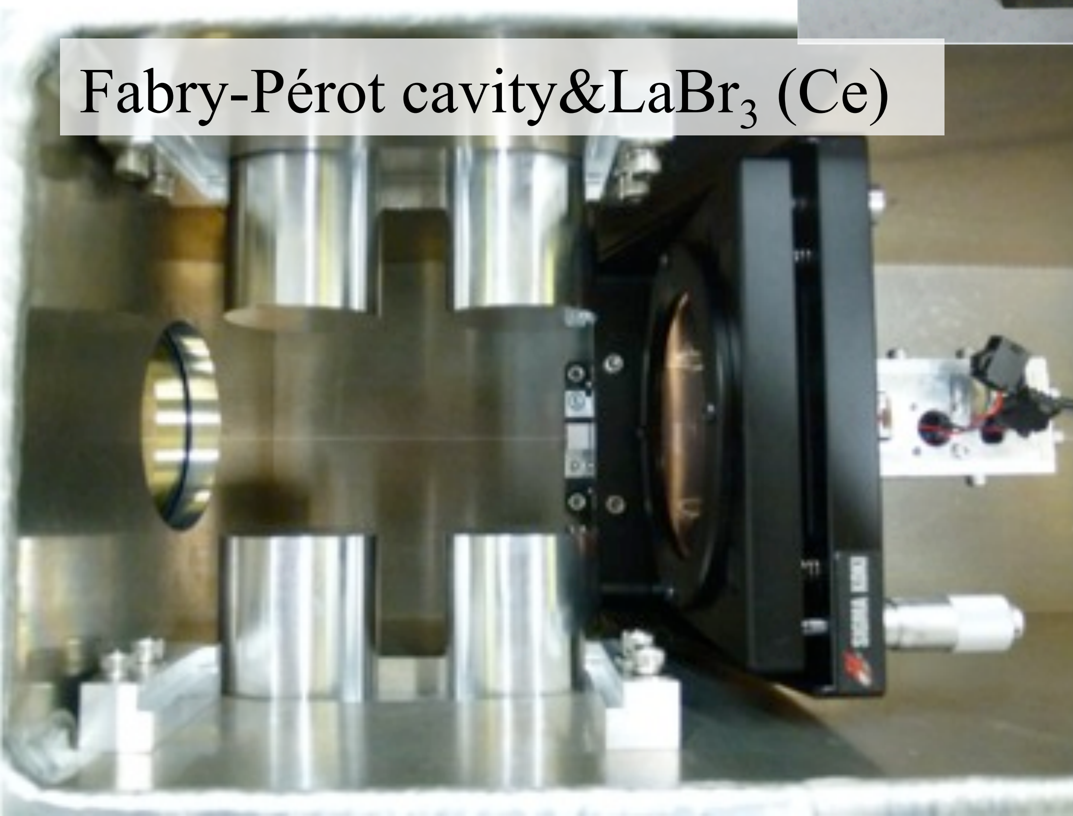
Strong E-field in the cavity accelerates positrons

→ Probability of Ps production increases → Big offset for the signal



Photograph of the gas chamber



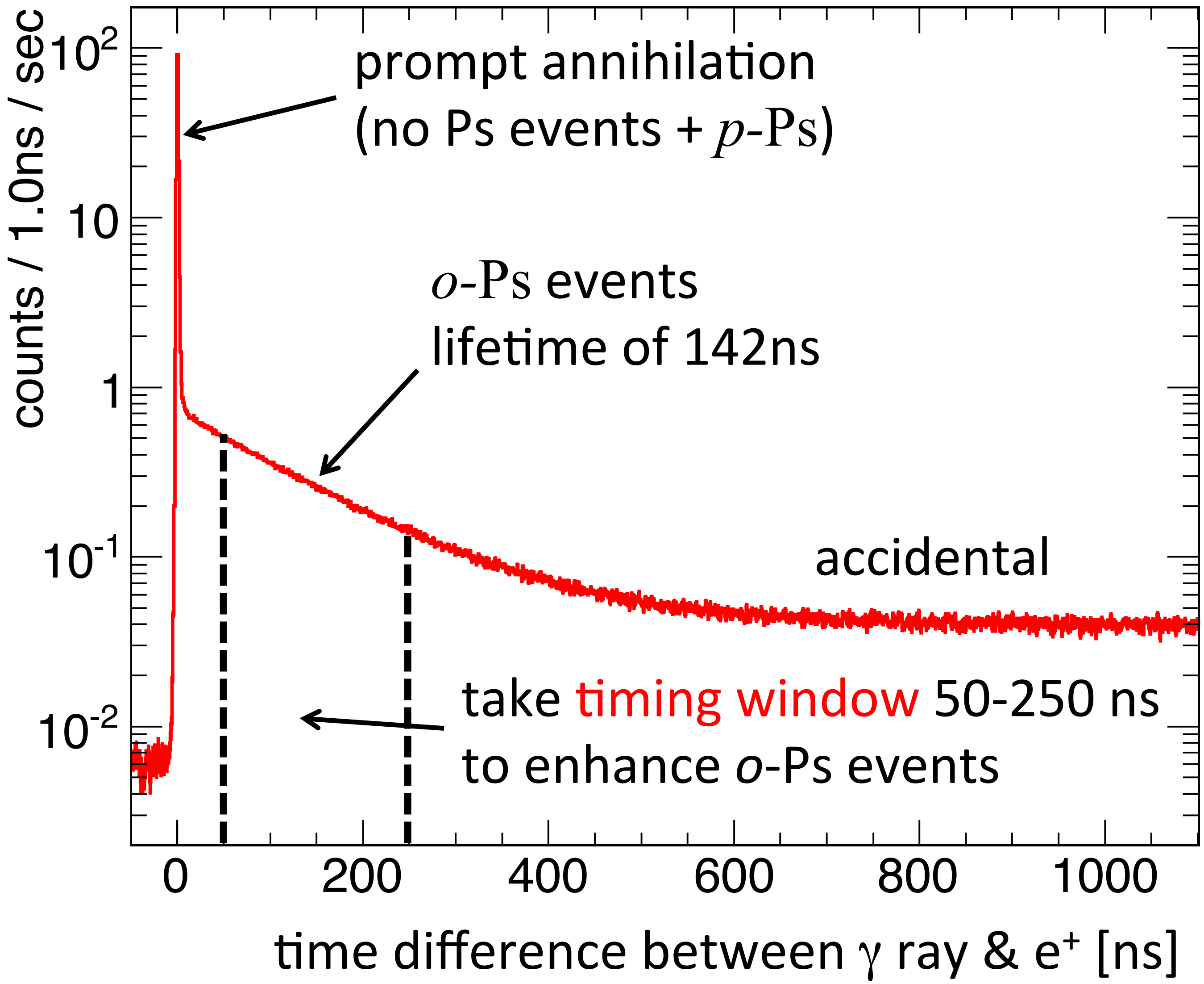


The silicon base for the mesh
- water-cooling
- window of the chamber
- light shielding

DATA ANALYSIS

Timing window

signal: o-Ps (long lifetime of 142ns)→*p*-Ps→2γ (back-to-back 511keV)

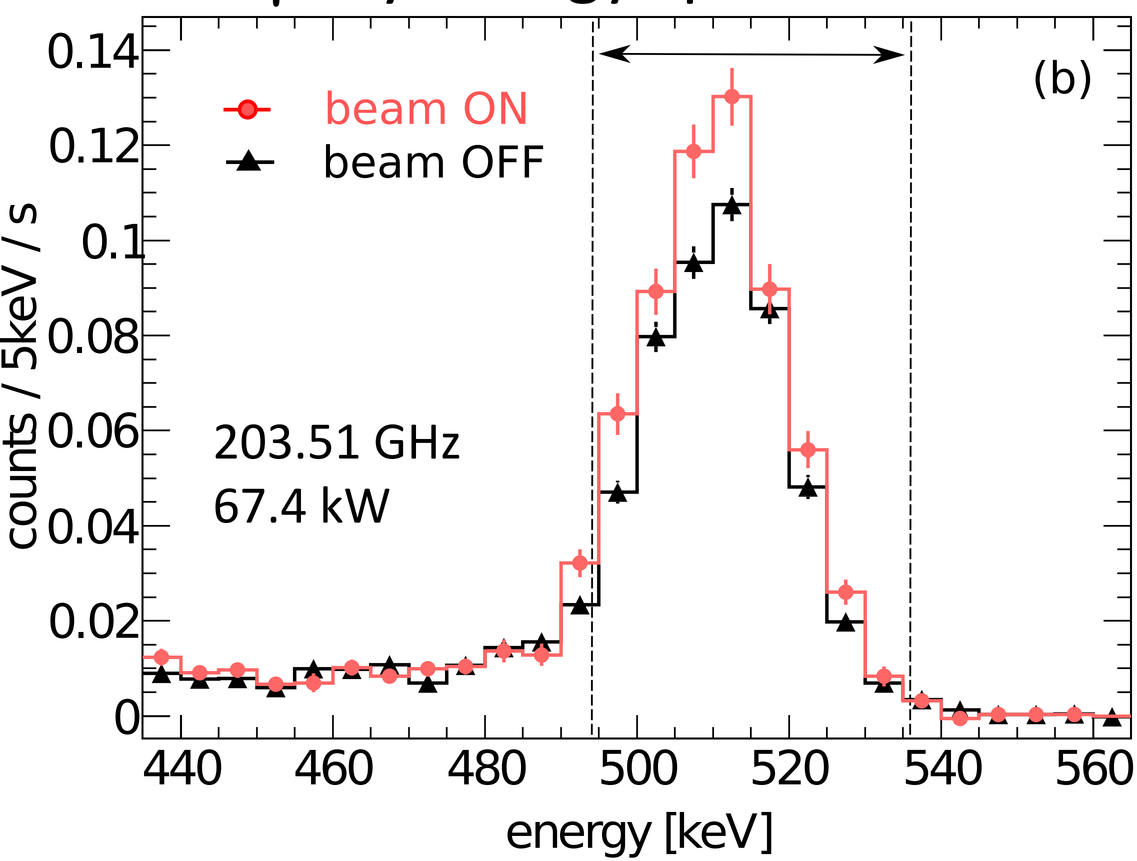


Energy cut & background estimation

signal: *o*-Ps (long lifetime of 142ns)→*p*-Ps→2γ (back-to-back 511keV)

Back-to-back and energy selection of 511 keV +3σ/-2σ
→enhance "→ 2γ" events

γ-ray Energy spectrum



- Remaining background

→ Make the gyrotron work in pulsed operation (duty ratio 30%, repetition rate 5Hz)

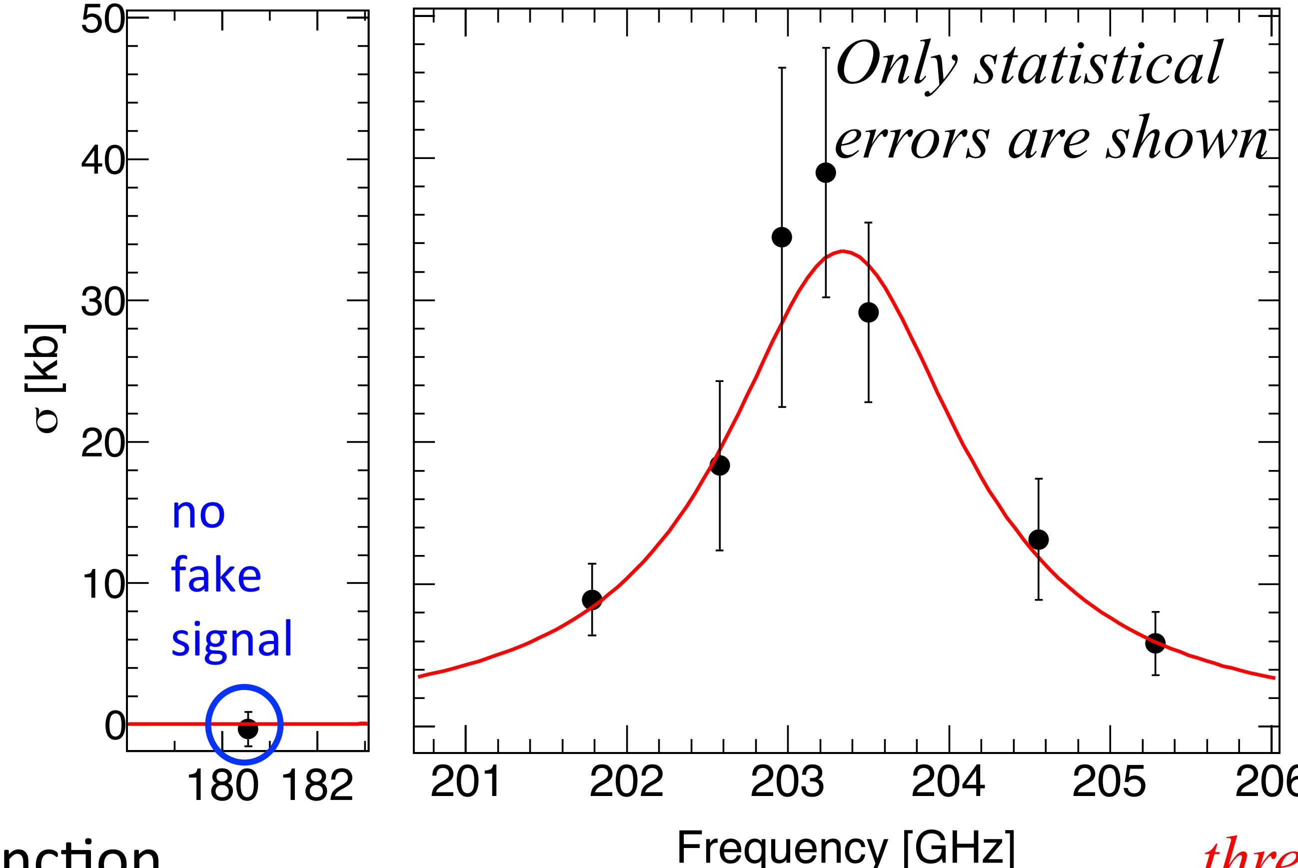
→ Use beam-OFF events to estimate background

<u>Significant signal</u>

(ON – OFF)
= 93.3 ± 14.4 mHz

Breit-Wigner Resonance

Transition signal (ON-OFF) is interpreted as cross-section σ of the resonance using P_{eff}, and Ps position distribution from MC simulations



Fitting function

$$g(\omega) = 3A\frac{\pi c^2}{\hbar^2\omega_0^2}\cdot\frac{1}{\pi}\frac{\Gamma/2}{(\omega-\omega_0)^2+(\Gamma/2)^2}$$

$$\omega_0 = 2\pi\Delta_{HFS}^{Ps}$$

$$\Gamma = A + \Gamma_{o\text{-}Ps} + \Gamma_{p\text{-}Ps} \sim \Gamma_{p\text{-}Ps}$$

three fitting parameters

Systematic uncertainties

Source	$\Delta_{\mathrm{HFS}}^{\mathrm{Ps}}$	$\Gamma_{\mathrm{p-Ps}}$	A
Power estimation	430 ppm	10.0 %	7.2 %
Stark effect	460 ppm	–	–
Monte Carlo simulation	280 ppm	5.5 %	3.0 %
Total	540 ppm	11.4 %	7.8 %

- Uncertainty of calibration factor C
- The Stark effect from gas molecules shifts Δ_{HFS}
- Monte Carlo simulation for widely spread Ps distribution

Results

value ± statistical error ± systematic error

Parameter	This experiment	Theory
$\Delta_{\mathrm{HFS}}^{\mathrm{Ps}}$ [GHz]	$203.39^{+0.15}_{-0.14} \pm 0.11$	$203.391\,91(22)$
$\Gamma_{\mathrm{p-Ps}}$ [ns^{-1}]	$11.2^{+1.9}_{-2.3} \pm 1.3$	(*) $7.9894\,76(13)$
A [$\times 10^{-8}\ \mathrm{s}^{-1}$]	$3.69 \pm 0.48 \pm 0.29$	(**) 3.37

(*) A. Kniehl, and A. A. Penin, Phys. Rev. Lett. 85, 1210 (2000);
K. Melnikov and A. Yelkhovsky, Phys. Rev. D. 62, 116003 (2000).

(**) P. Wallyn, et al., Astrophys. J. 465, 473 (1996).

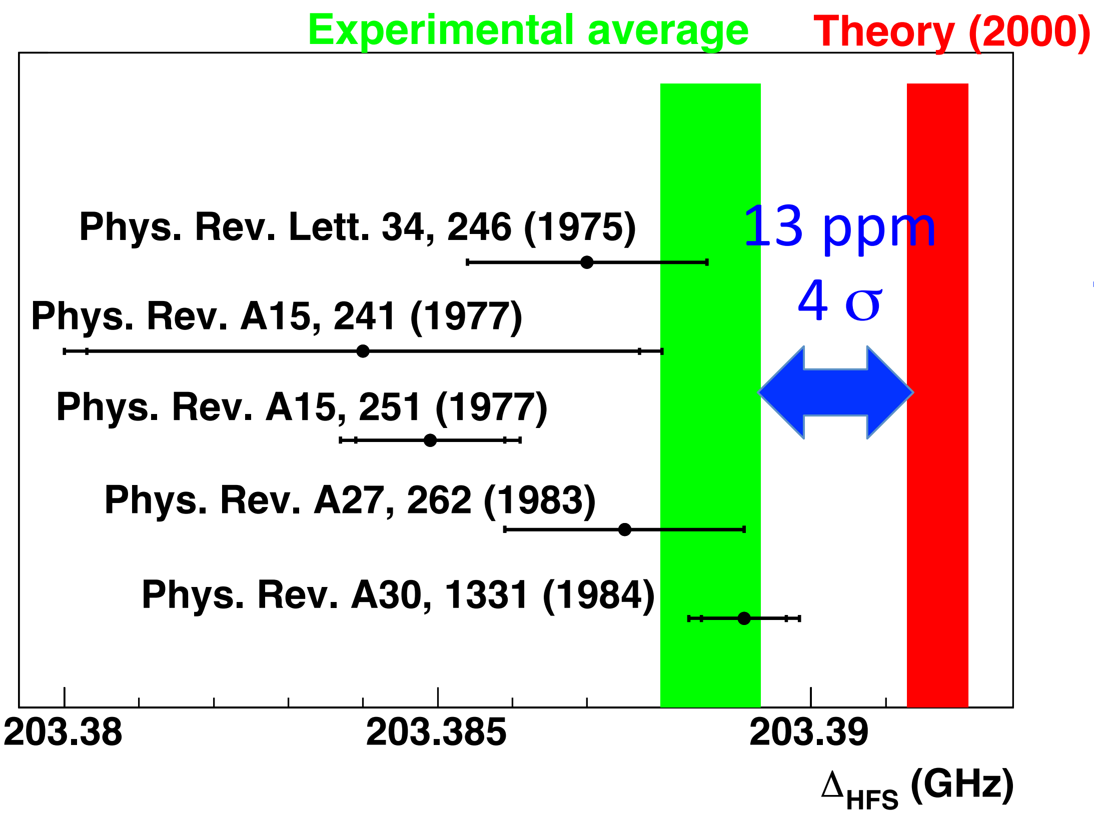
These 2 parameters are firstly determined with a direct way.

☆We firstly demonstrate Δ_{HFS} can be directly determined!

PROBLEM IN HYPERFINE STRUCTURE & FUTURE PROSPECT

Displacement

Higher order QED corrections up to $O(\alpha^3 \ln \alpha^{-1})$ are available in 2000.
Results of some $O(\alpha^3)$ diagrams were reported (c.f. prof. Adkins).



4σ Discrepancy!

Possible reasons

i) **Magnetic field**
ii) **Material effect**
iii) **(QED)**
iv) **Physics BSM**

→Study of systematic uncertainties is required

Theoretical papers:

B.A. Kniehl et al. Phys. Rev. Lett. 85, 5094 (200)
K. Melnikov et al., Phys. Rev. Lett. 86, 1498 (2001)
R.K. Hill, Phys. Rev. Lett. 86, 3280 (2001)
M. Baker, et al. Phys. Rev. Lettt. 112, 120407 (2014)
G.S. Adkins et al., Phys. Rev. A 89, 052518 (2014)

Some recent studies

Y. Sasaki and AM et al, Phys. Lett. B 697 121 (2011)

- Quantum oscillation between Zeeman shifted levels
- 200 ppm accuracy but shown to be improved to 10 ppm level

D.B. Cassidy et al, Phys. Rev. Lett. 109 073401 (2012)

- Saturation absorption spectroscopy between Zeeman shifted 1S and 2P levels
- 2% accuracy but promising improvements because of established laser technology

A. Ishida et al, Phys. Lett. B 734 338 (2014)

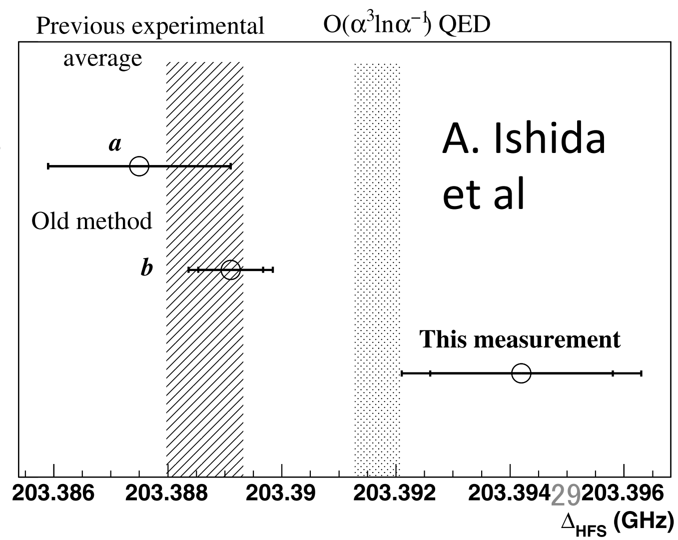
- Conventional method i.e. transition between Zeeman shifted 1S levels by RF

i) Uniform B-field with a big SC solenoid (ϕ80cm).

ii) An interpolation to vacuum is studied considering slow thermalization of Ps in gas (Ps is more energetic than thermal temperature for long time).

→ favors QED by 2.7σ

☆Direct measurement can be a complementary check of methods using the Zeeman effect.



Toward precision measurement

The discrepancy 13 ppm < current accuracy 900 ppm

Three major improvements

- Positron beam for better statistics (x10^4)
  - Well collimated beam can improve fraction of positrons existing in the Fabry-Pérot cavity [10^8 Hz >> 10^3 Hz from ^{22}Na source (1MBq)]
  - Positron beam and Ps converter are available in KEK
- Ps is formed in vacuum to eliminate gas effects
  - Efficient Ps converter (a material in which e^+ is converted to Ps extracted into vacuum; such as heated alumina efficiency=50%)
  - No stark effect and non-thermalization effect of Ps
- MW-class gyrotron
  - No Fabry-Pérot cavity → Much better power estimation (0.3%) by temperature increase of water-flow for cooling power dump
  - Well controlled power (<1%)

Estimated future uncertainties

Source	$\Delta^{\mathrm{Ps}}_{\mathrm{HFS}}$
Statistics	5 ppm
Power estimation	3 ppm
Power control	4 ppm
Frequency stability	< 1 ppm
Power stability	4 ppm
Doppler shift	1 ppm
Total	8 ppm

- Uncertainty from the magnetic field can be the largest systematic uncertainty for the Zeeman-type measurement in vacuum
- Instead of the magnetic field, systematic uncertainties from millimeter waves can be dominant in the direct measurement.

→They are complementary with each other.

Conclusion

- Though Ps is a good system to study QED, its hyperfine structure has never been directly measured because of difficulties regarding the use of millimeter waves.
- We developed new millimeter-wave devices: gyrotron and Fabry-Pérot cavity; Δ_{HFS} was firstly measured with the direct transition method.
- value: $\Delta_{\mathrm{HFS}}^{\mathrm{Ps}} = 203.39^{+0.15}_{-0.14}\,(\mathrm{stat.}) \pm 0.11\ (\mathrm{syst.})\ \mathrm{GHz}$
- p-Ps decay width was also measured
- value: $\Gamma_{\mathrm{p\text{-}Ps}} = 11.2^{+1.9}_{-2.3}\,(\mathrm{stat.}) \pm 1.3\ (\mathrm{syst.})\ \mathrm{ns}^{-1}$
- arXiv:1403.0312
- PhD thesis: http://www.icepp.s.u-tokyo.ac.jp/papers/ps/thesis/doctor/miyazaki_thesis.pdf

  (It will be published by Springer Thesis in one year)