Measurement of Hyperfine Splitting of Positronium

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Outline

Positronium Hyperfine Splitting (Ps-HFS)

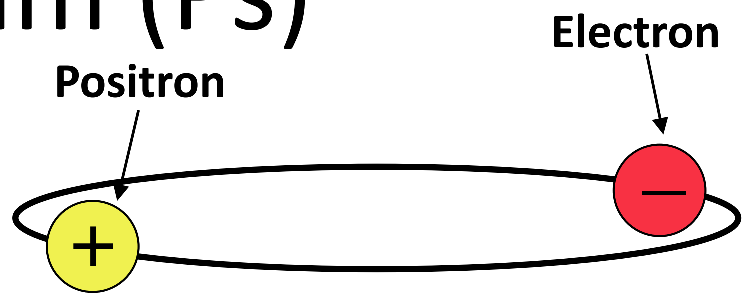
A. Ishida

1. Indirect Measurement
- Our new experiment
- Prototype run and its results
- Prospects & Current status

T. Yamazaki

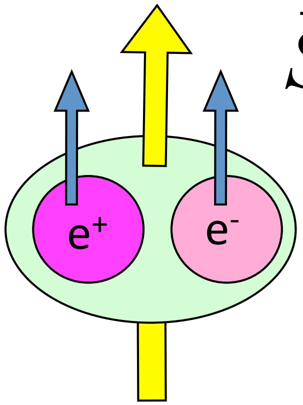
2. Direct Measurement
- Experimental Concept: First Direct Measurement of Ps-HFS
- Experimental setup
- Expected performance

Positronium (Ps)



- Bound state of an electron (e^-) and a positron (e^+)
  - Purely leptonic system (free from hadronic uncertainties)
  - The lightest hydrogen-like "atom"
  - Bound state of particle and antiparticle → Sensitive to new physics beyond the Standard Model.
- Described by bound-state QED.

Two Spin Eigenstates of Positronium



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

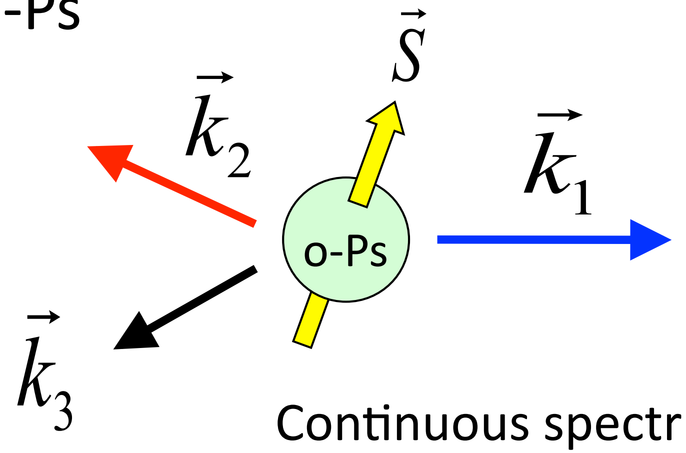
Ortho-positronium (o-Ps)

Spin=1 The same quantum number as photon

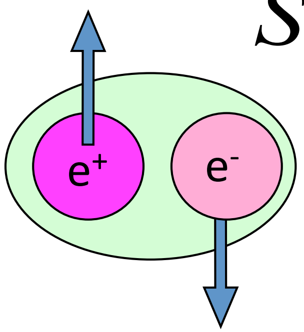
o-Ps → 3γ (, 5γ, …)

o-Ps

Lifetime 142 ns



Continuous spectrum



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

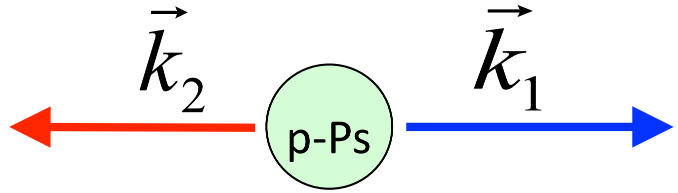
Para-positronium (p-Ps)

Spin=0 Scalar particle

p-Ps → 2γ (, 4γ, …)

p-Ps

Lifetime 125 ps



Monochromatic 511 keV

Positronium Hyperfine Splitting (Ps-HFS)

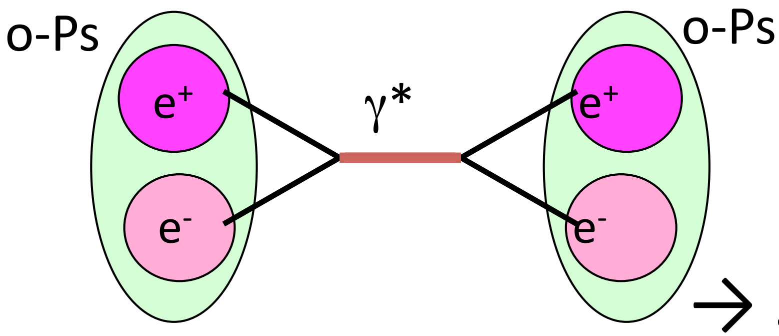
Energy difference between two spin eigenstates of the ground state Ps → Ps-HFS

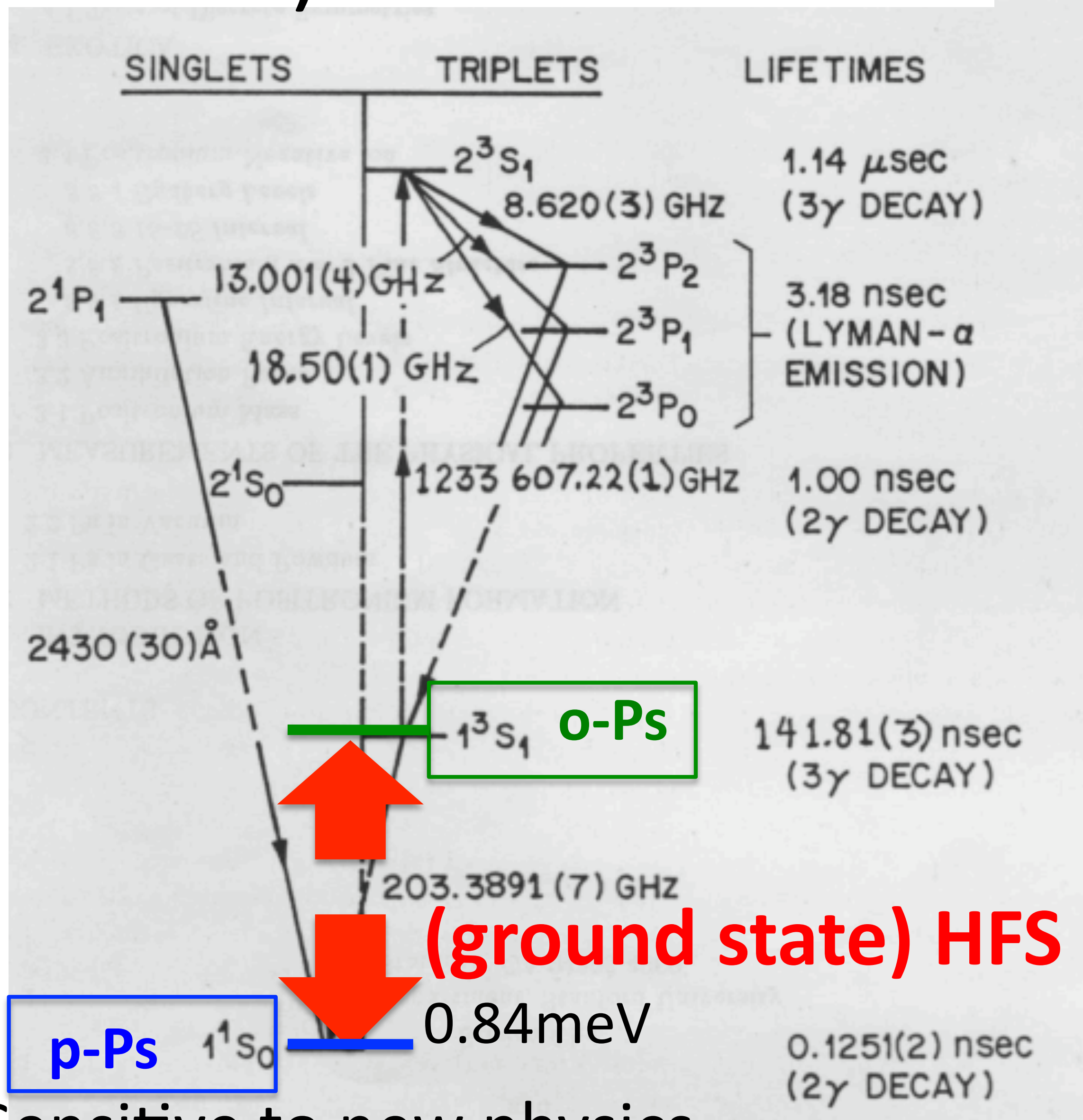
Large value of Ps-HFS 203 GHz
(cf. Hydrogen HFS 1.4 GHz)

1. Large spin-spin interaction

$$\vec{\mu} = \frac{e}{2m}\vec{\sigma}$$ (small mass)

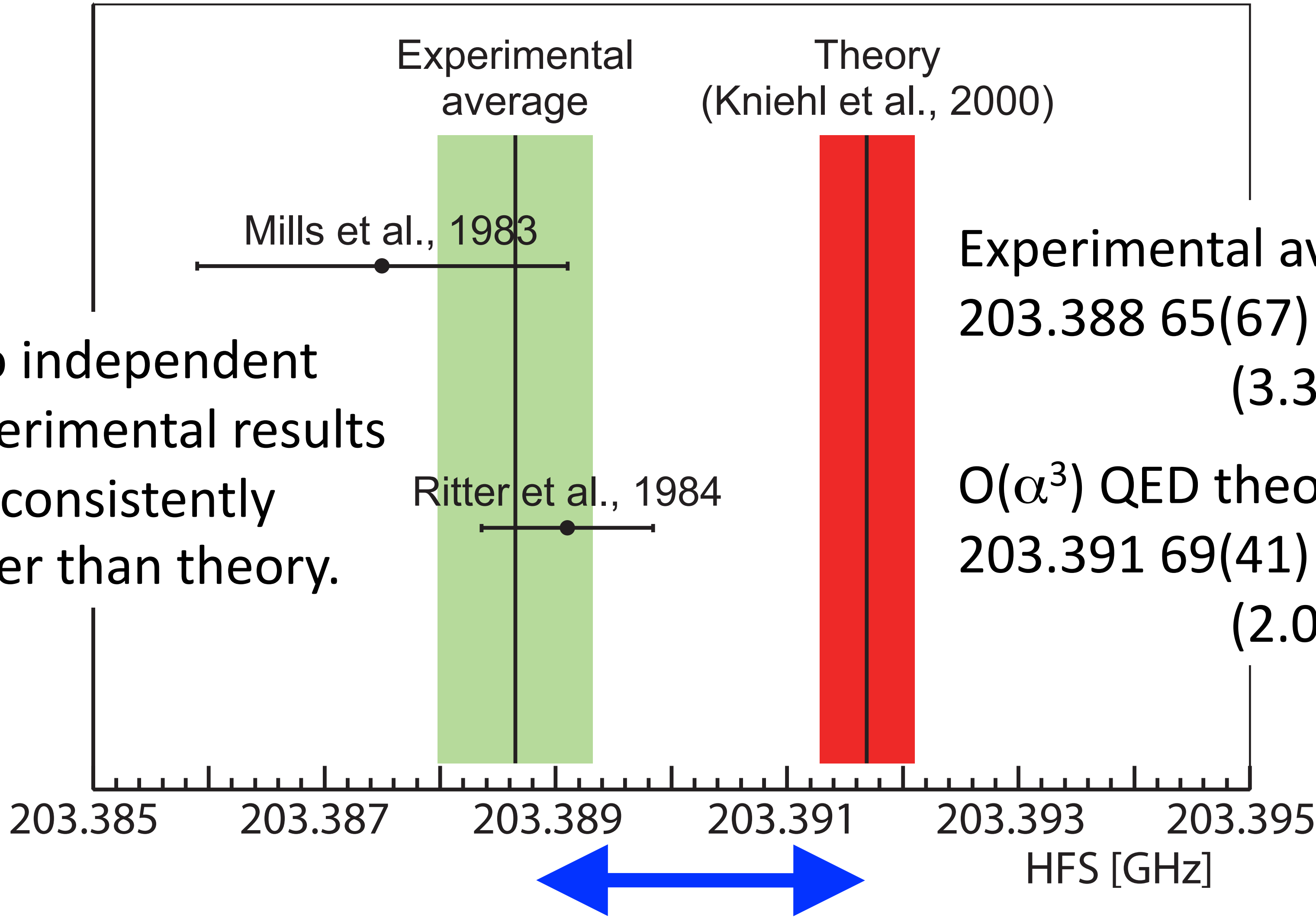
2. Contribution of Quantum oscillation in higher order correction





→ Sensitive to new physics

Discrepancy Between Experiments and Theory



Two independent experimental results are consistently lower than theory.

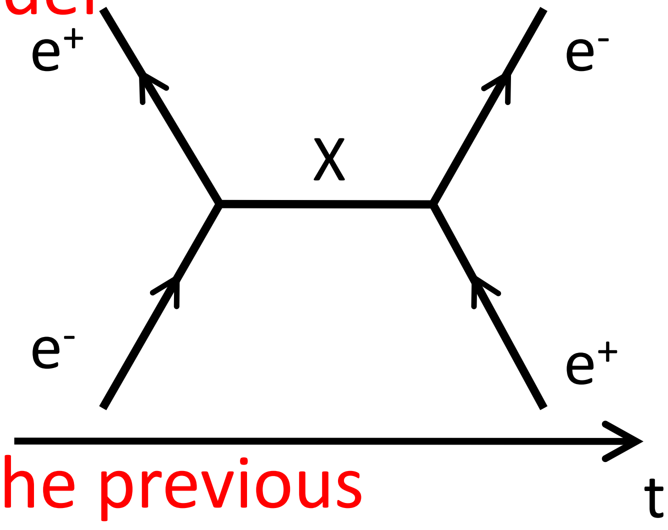
Experimental average
203.388 65(67) GHz
(3.3 ppm)

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

15 ppm (3.9 σ) discrepancy

Possible reasons for the discrepancy

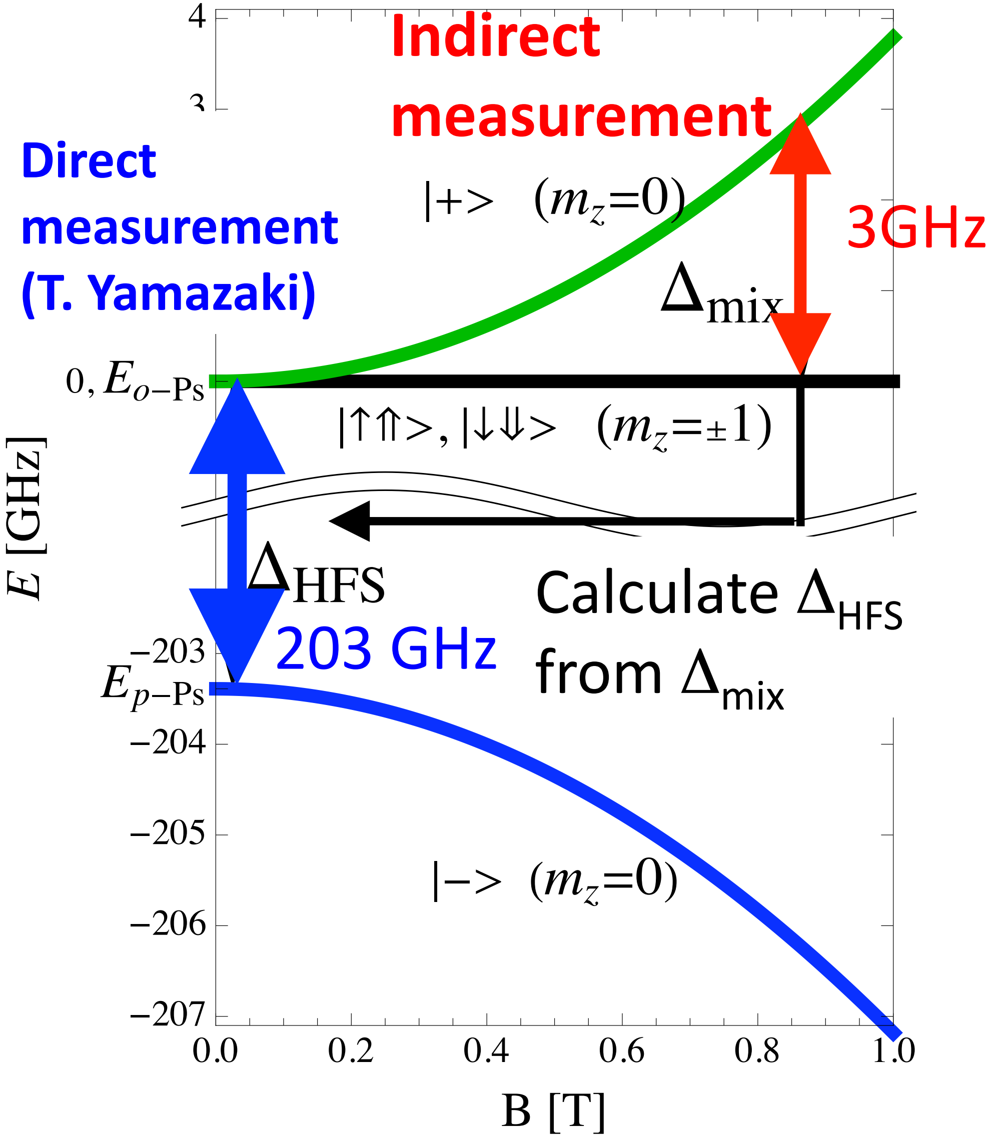
- New physics beyond the Standard Model
  - Weak interacting unknown particle
  - Sensitive to light particle (s-channel)
    (ex. O(MeV), $\alpha \sim 10^{-8}$ pseudo scalar)
  - o-Ps is sensitive to extra dimensions



- 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

1. Indirect Measurement

Experimental Technique
Indirect Measurement using Zeeman Effect



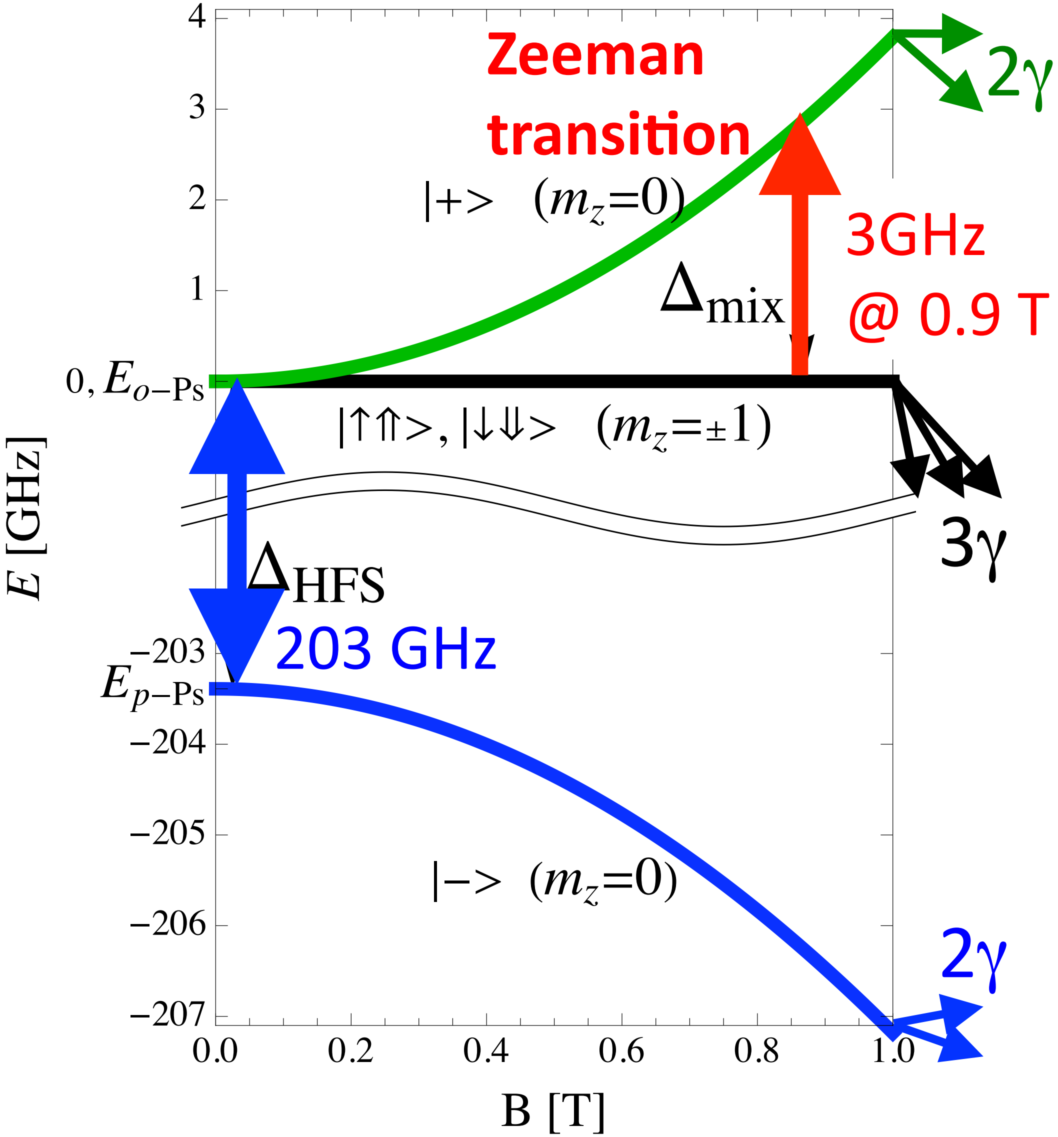
In a static magnetic field, the **p-Ps** state mixes with the **m_z=0 state of o-Ps** (Annihilate into 2 γ-rays).

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

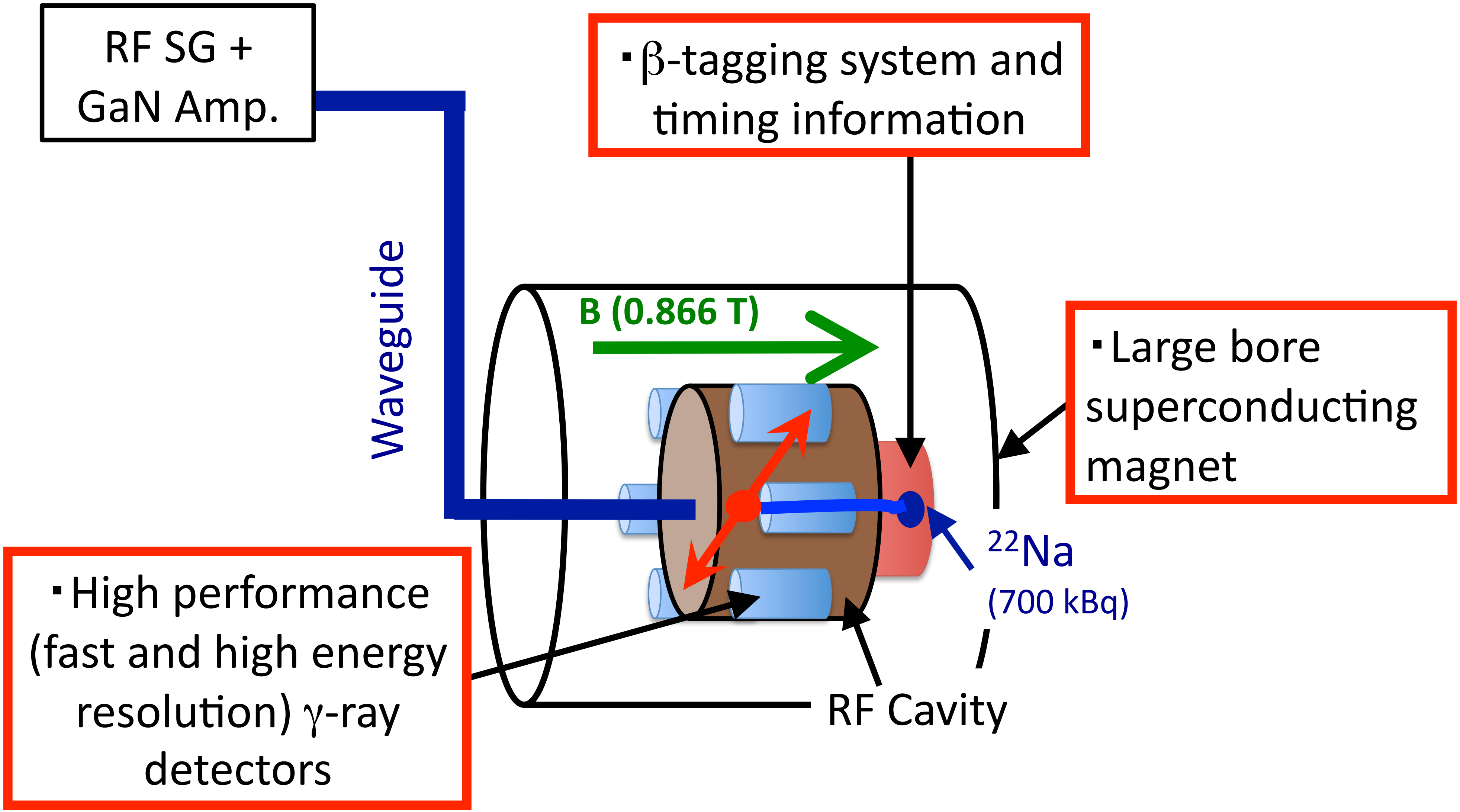


When a microwave field with a frequency of Δ_{mix} is applied, transitions between the m_Z=0 and m_Z=±1 states of o-Ps are induced.

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

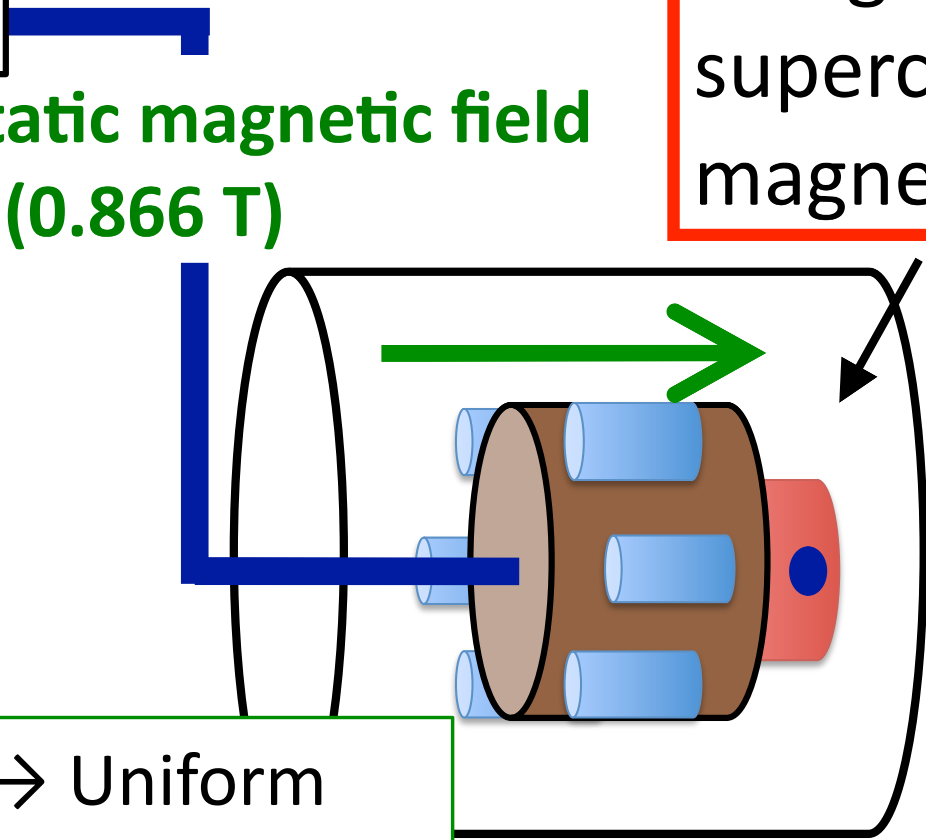
→This is the same approach as previous experiments.

Our New Experiment

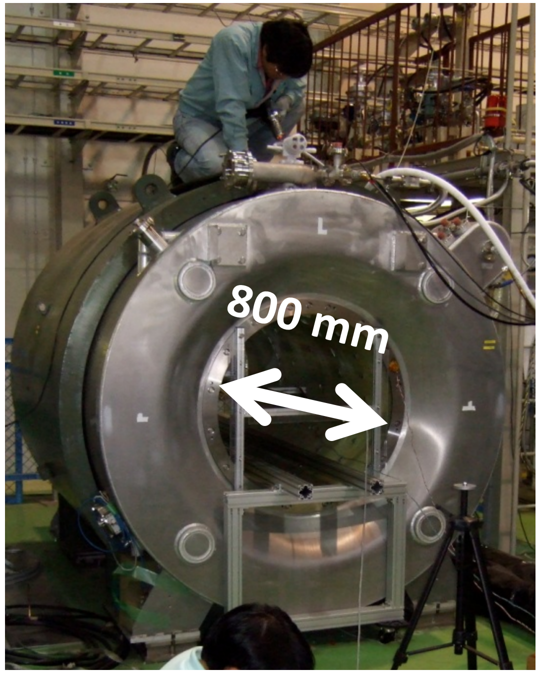


Our New Experiment

RF SG +
GaN Amp.



- Large bore superconducting magnet



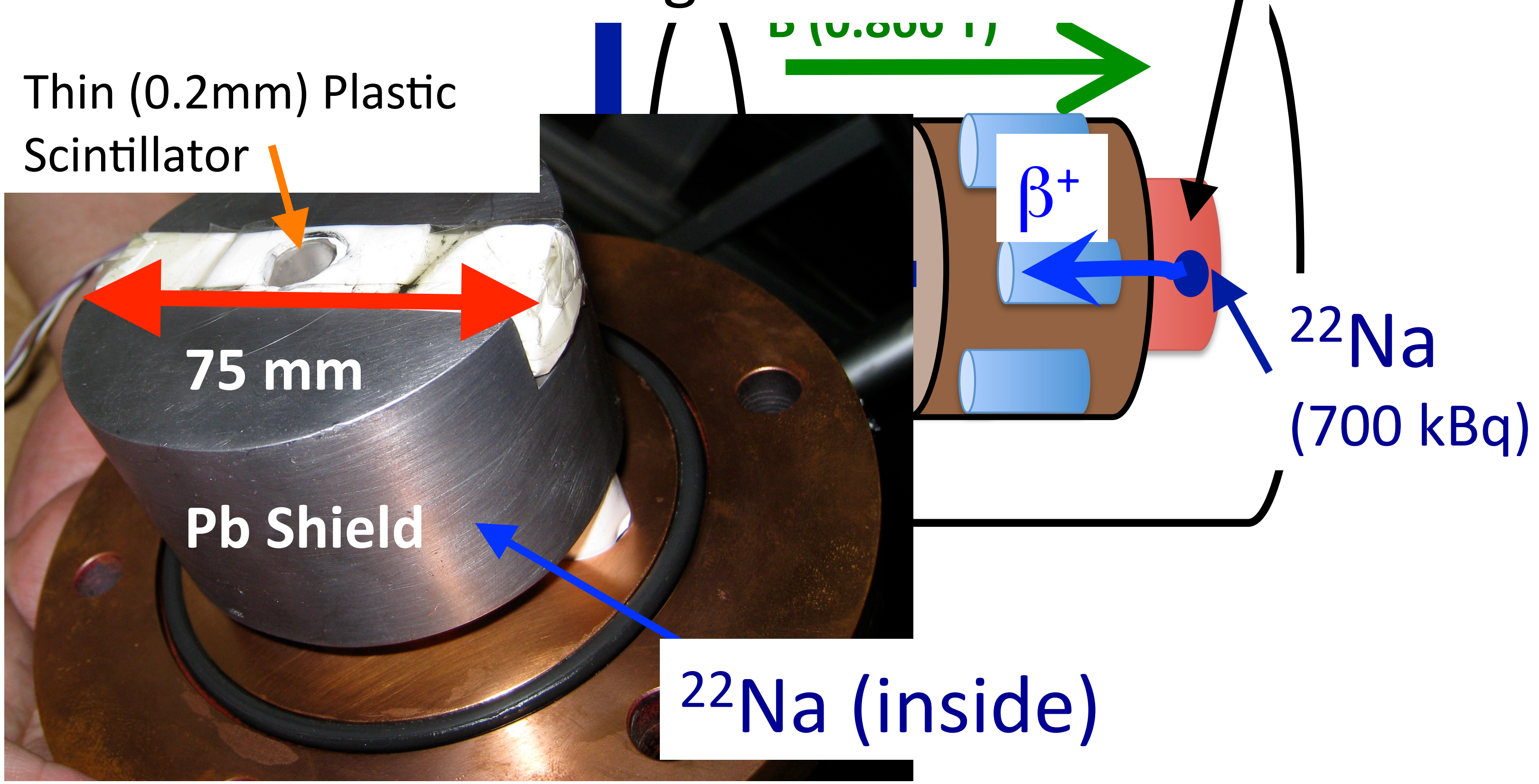
Large size → Uniform
Persistent Current mode
→ Stable

Our New Experiment

- β-tagging system and timing information

(1) Prompt suppression (→ Next page)

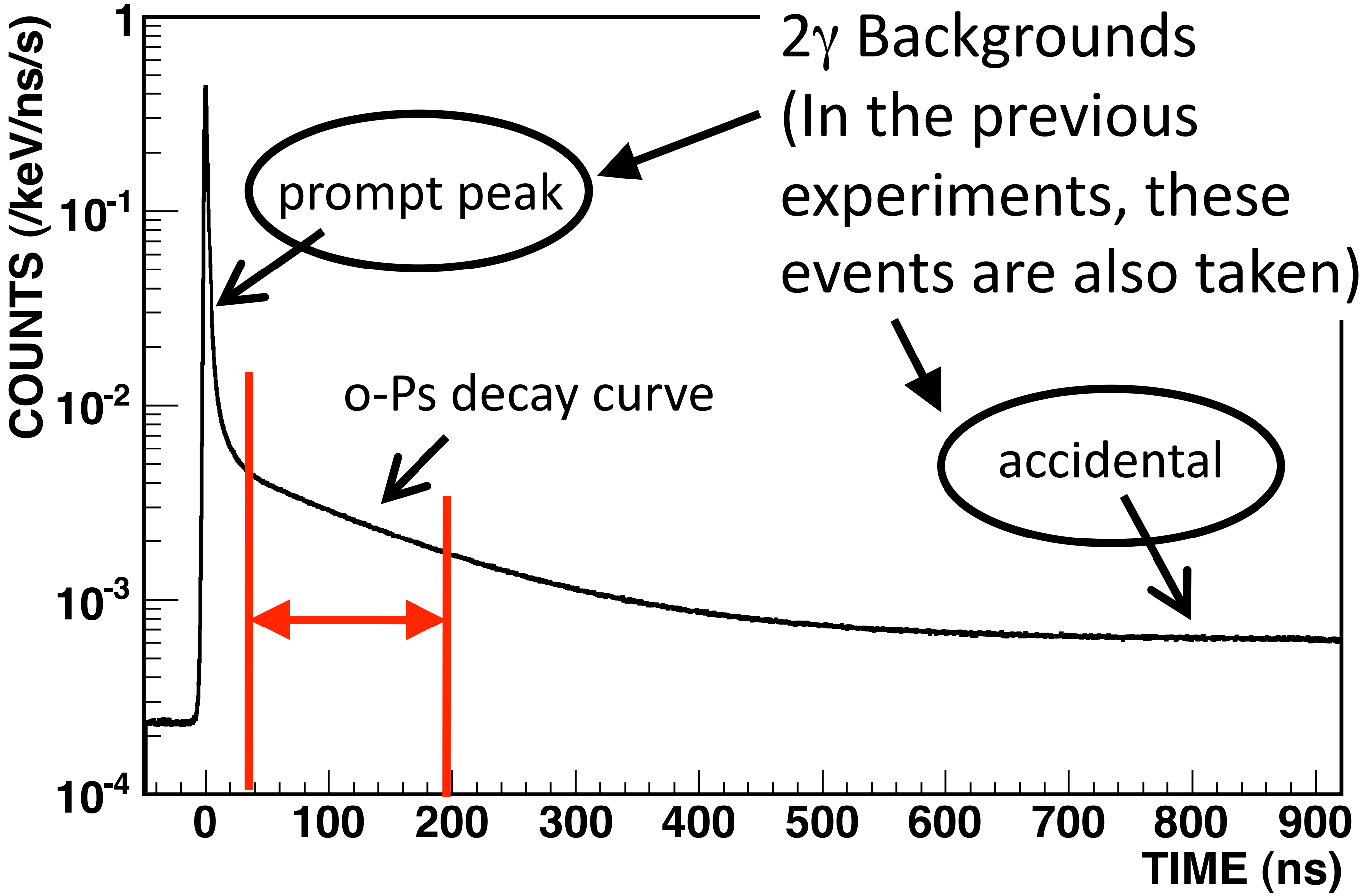
(2) Necessary for material effect estimation including Ps thermalization



Prompt Suppression

High S/N

Decay curve of Ps

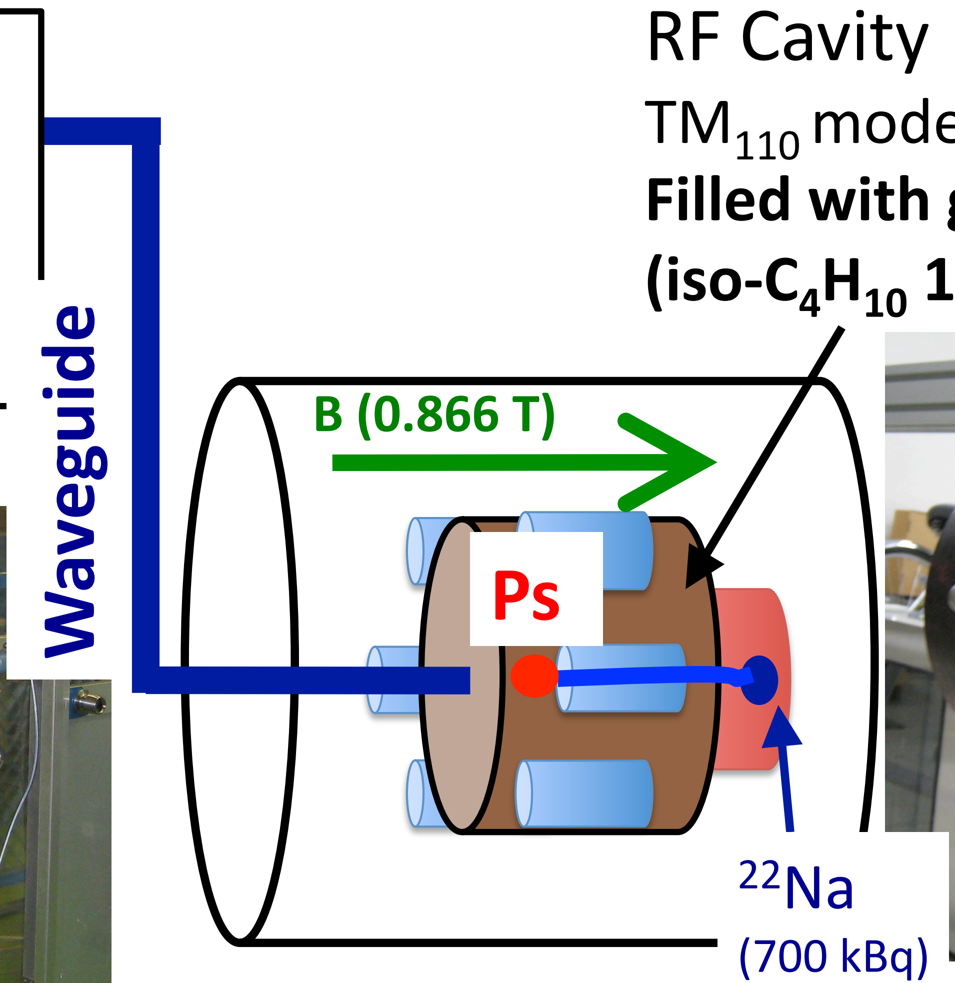


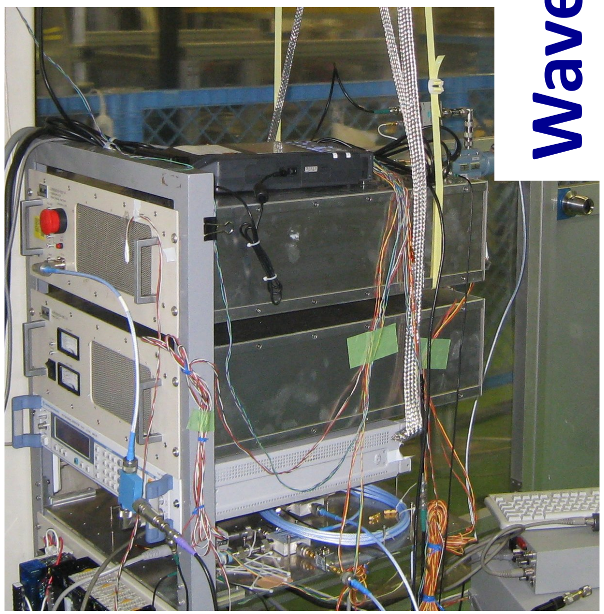
2γ Backgrounds (In the previous experiments, these events are also taken).

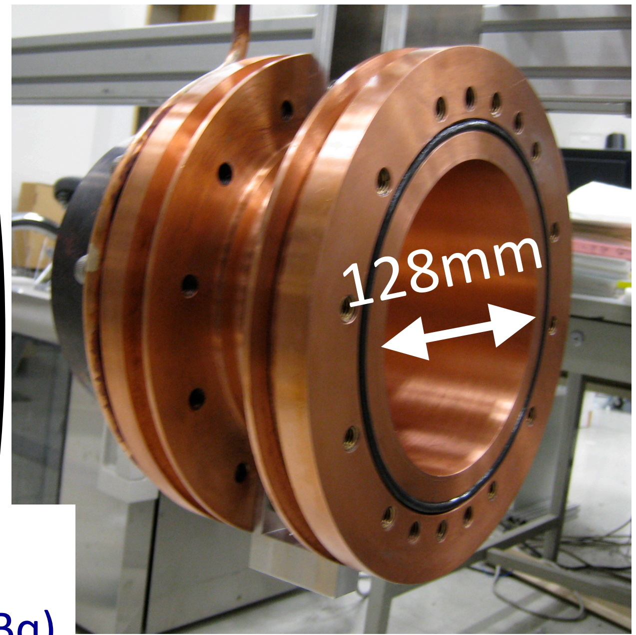
Select the o-Ps events (and Zeeman transition events) with

Timing window → About 20 times higher S/N

Our New Experiment



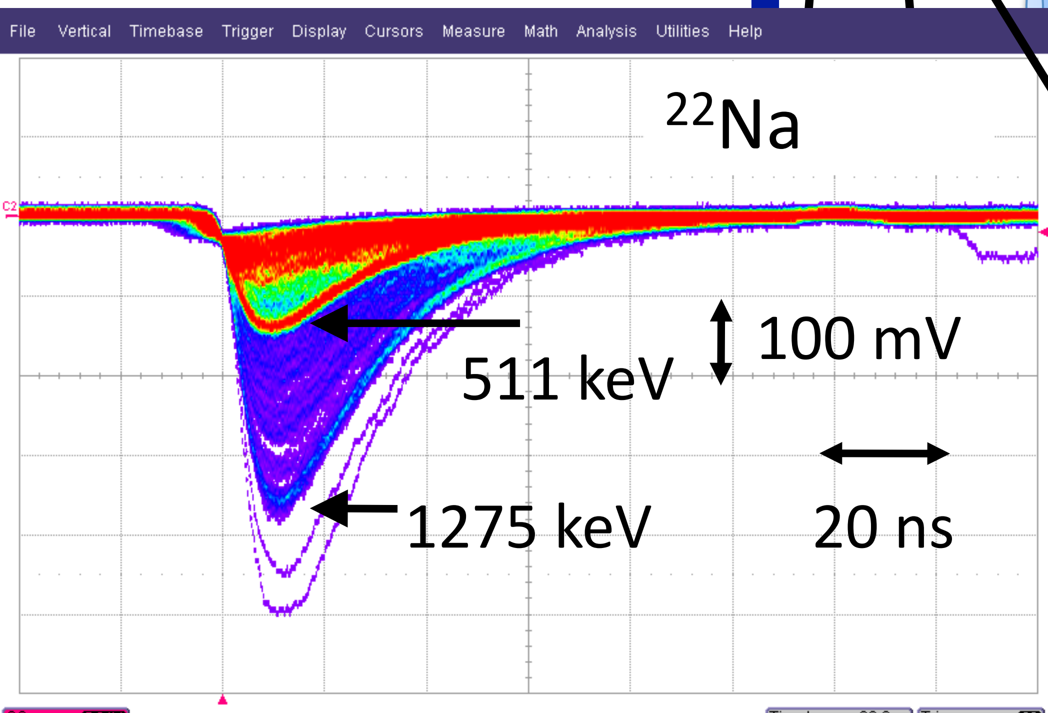


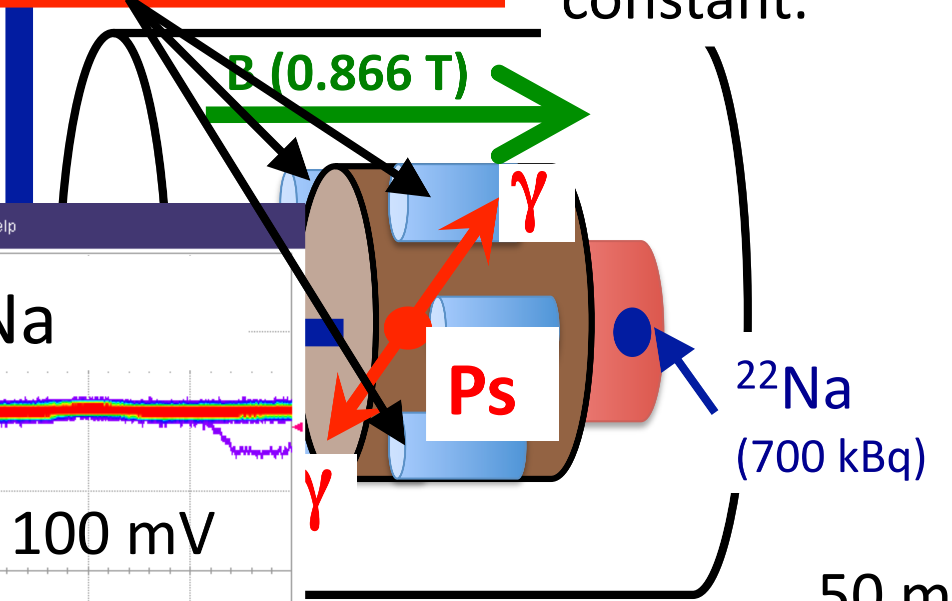


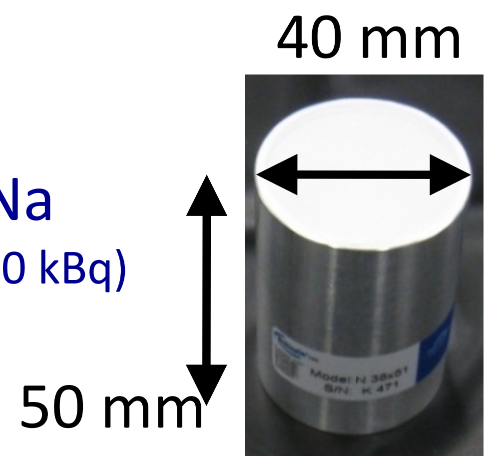
Our New Experiment

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

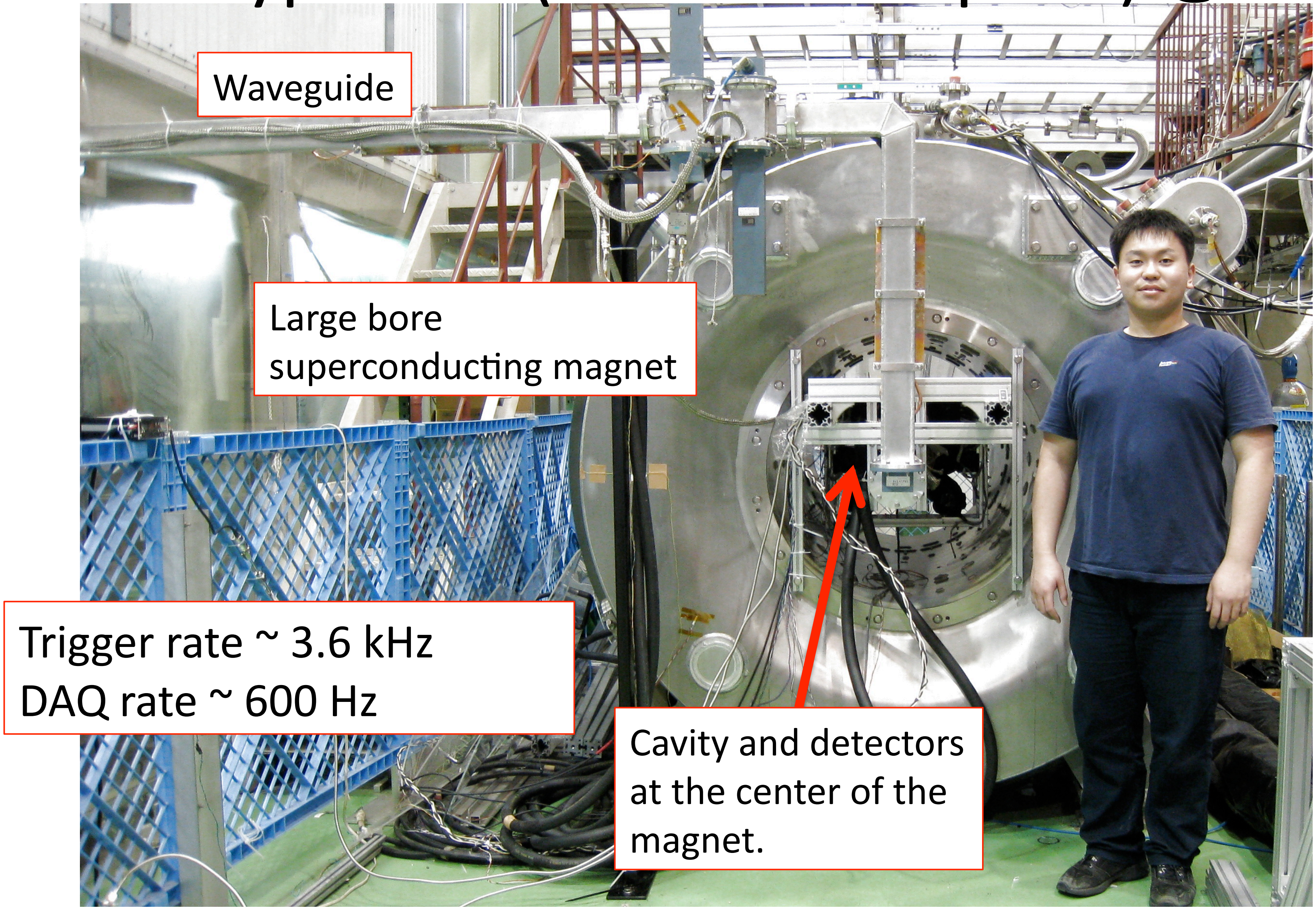
-**$LaBr_3(Ce)$ scintillators** x 6
-**High energy (4%) and timing (200 ps) resolutions**, short (16 ns) decay constant.



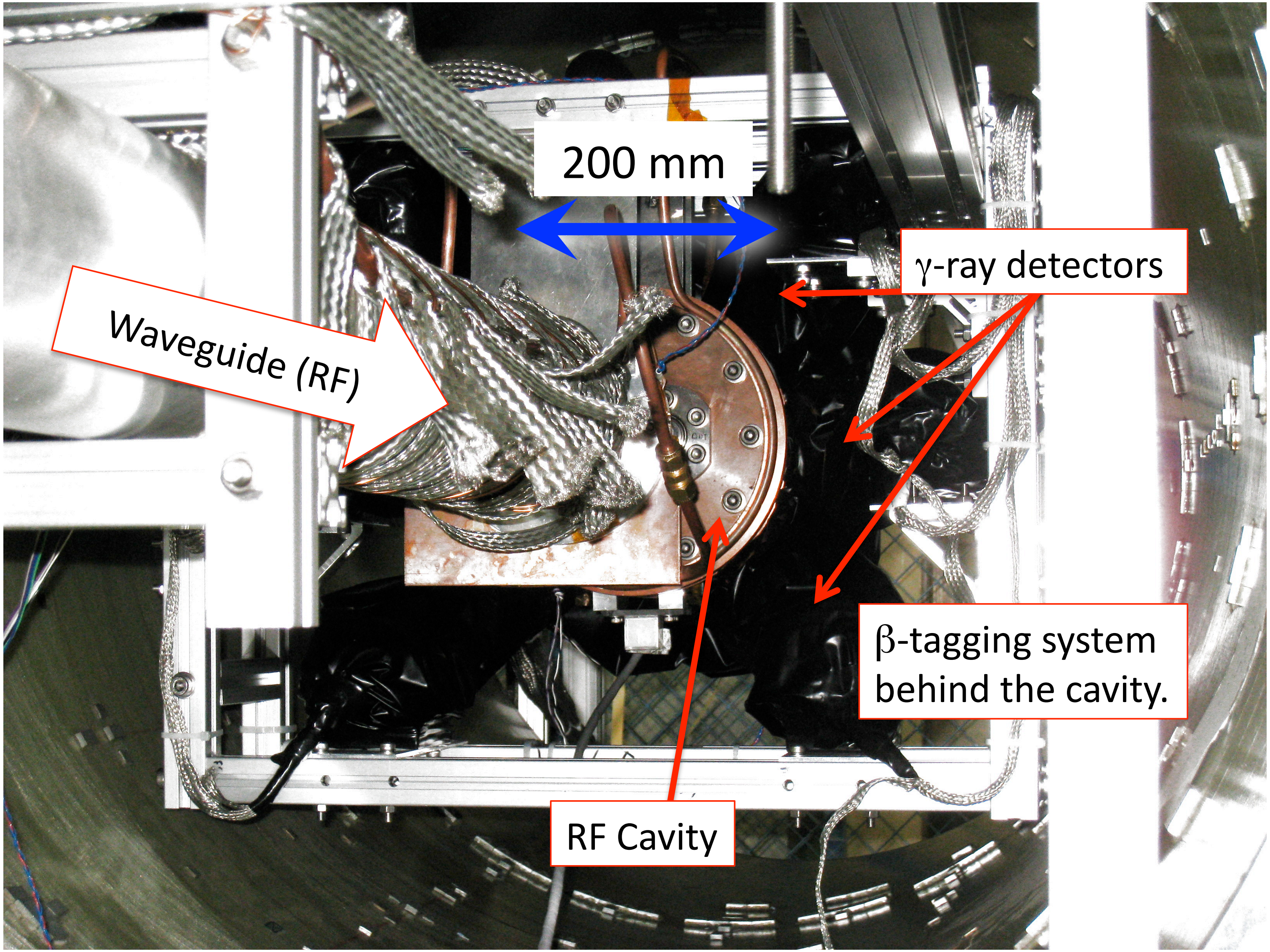




Our Experimental Setup
Prototype Run (2 Jul – 24 Sep ’09) @KEK



Center of the Magnet

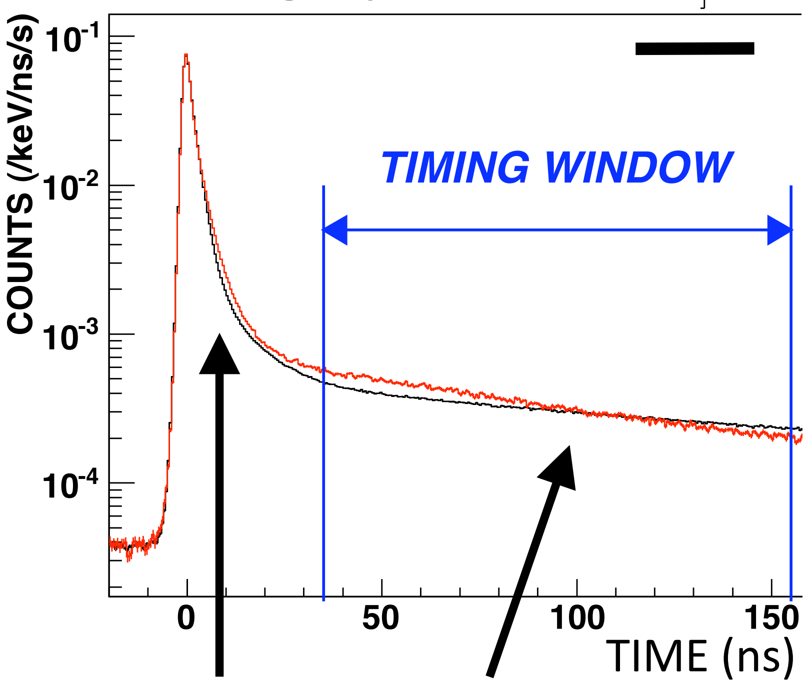


Analysis

Timing Spectra

ON Resonance RF ON

ON Resonance RF OFF



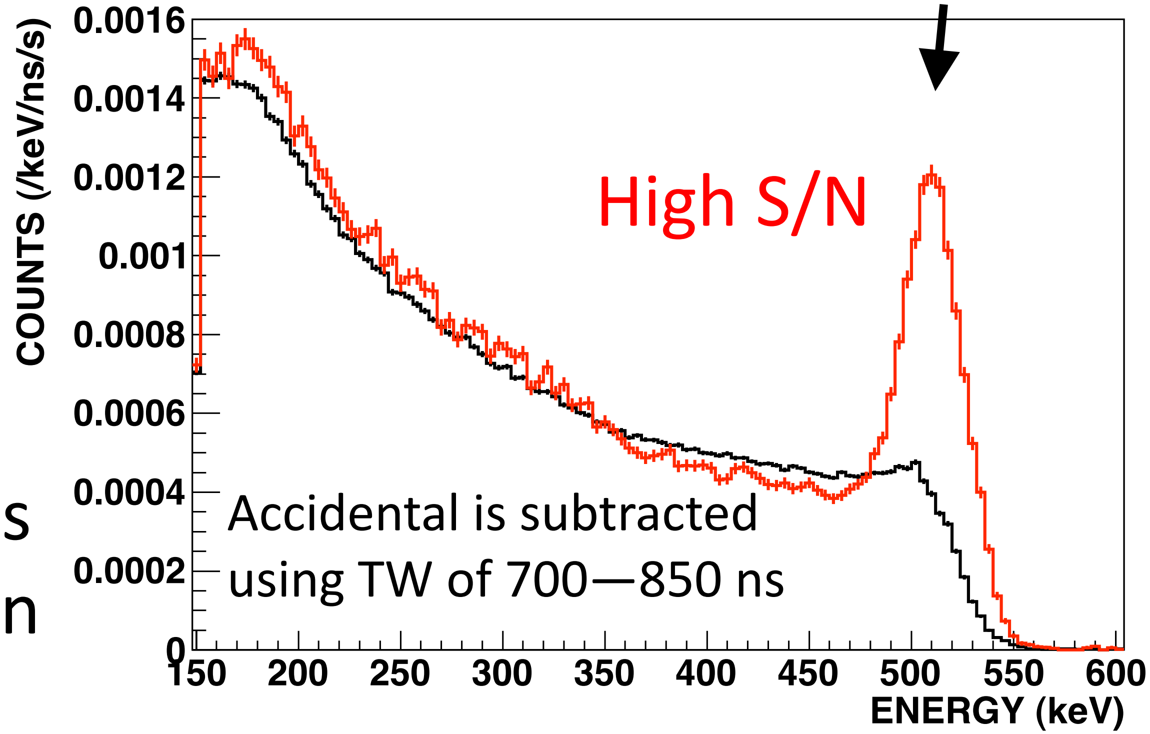
Short Component ($m_z = 0$)

Long Component ($m_z = \pm1$)

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

Energy Spectra

511 keV



2γ decay rate increases because of the Zeeman transition.

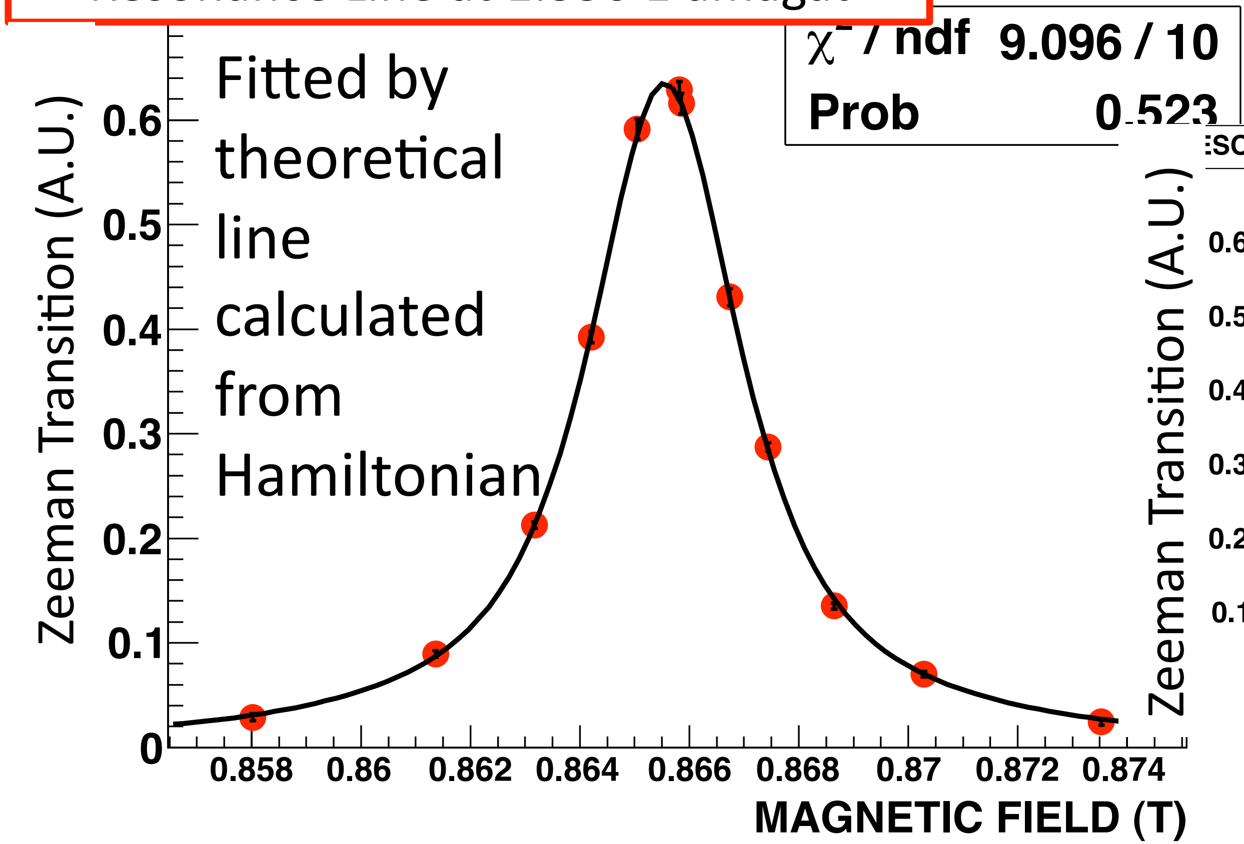
Resonance Lines

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

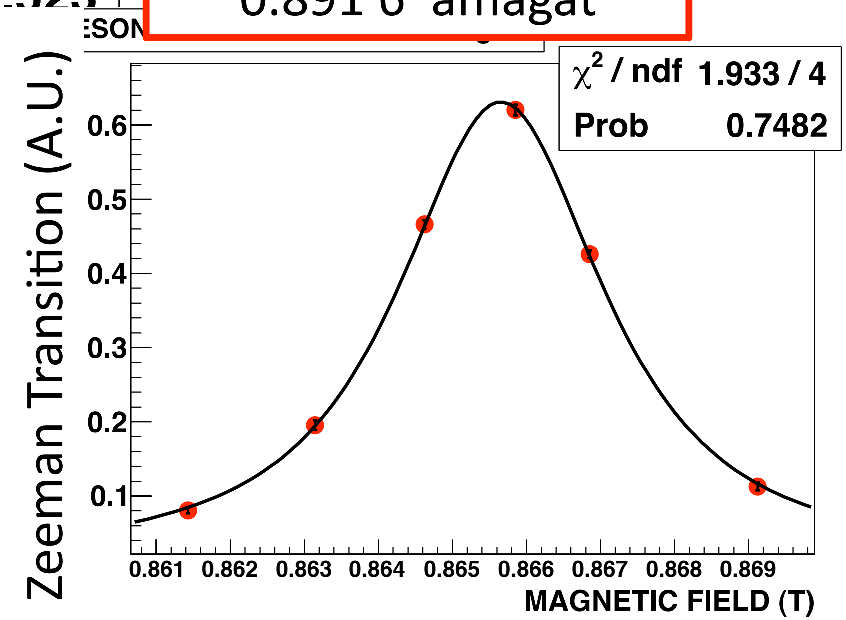
$2\gamma/3\gamma$ decay ratio is taken to be a Zeeman transition amount.

Resonance Line at 1.350 1 amagat

Fitted by theoretical line calculated from Hamiltonian



Resonance Line at 0.891 6 amagat

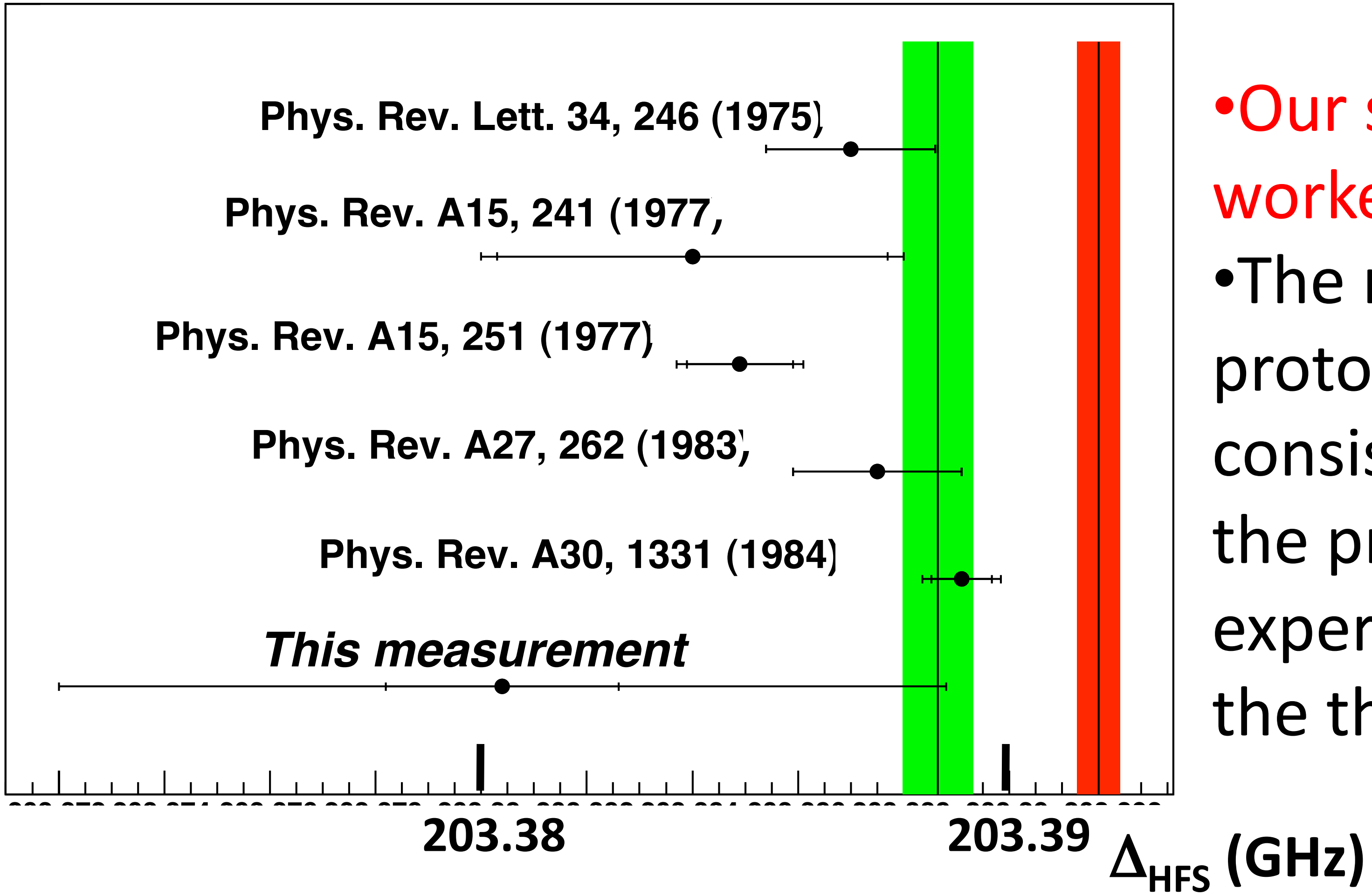


Δ_{HFS} = 203.368 3(55) GHz (27 ppm)

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:

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

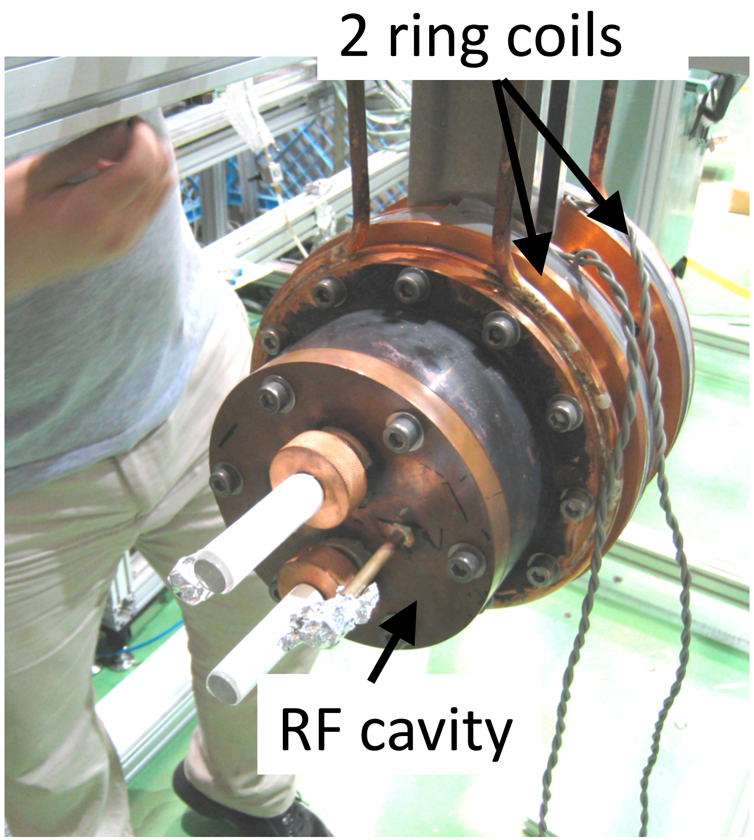
Systematic Errors

	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

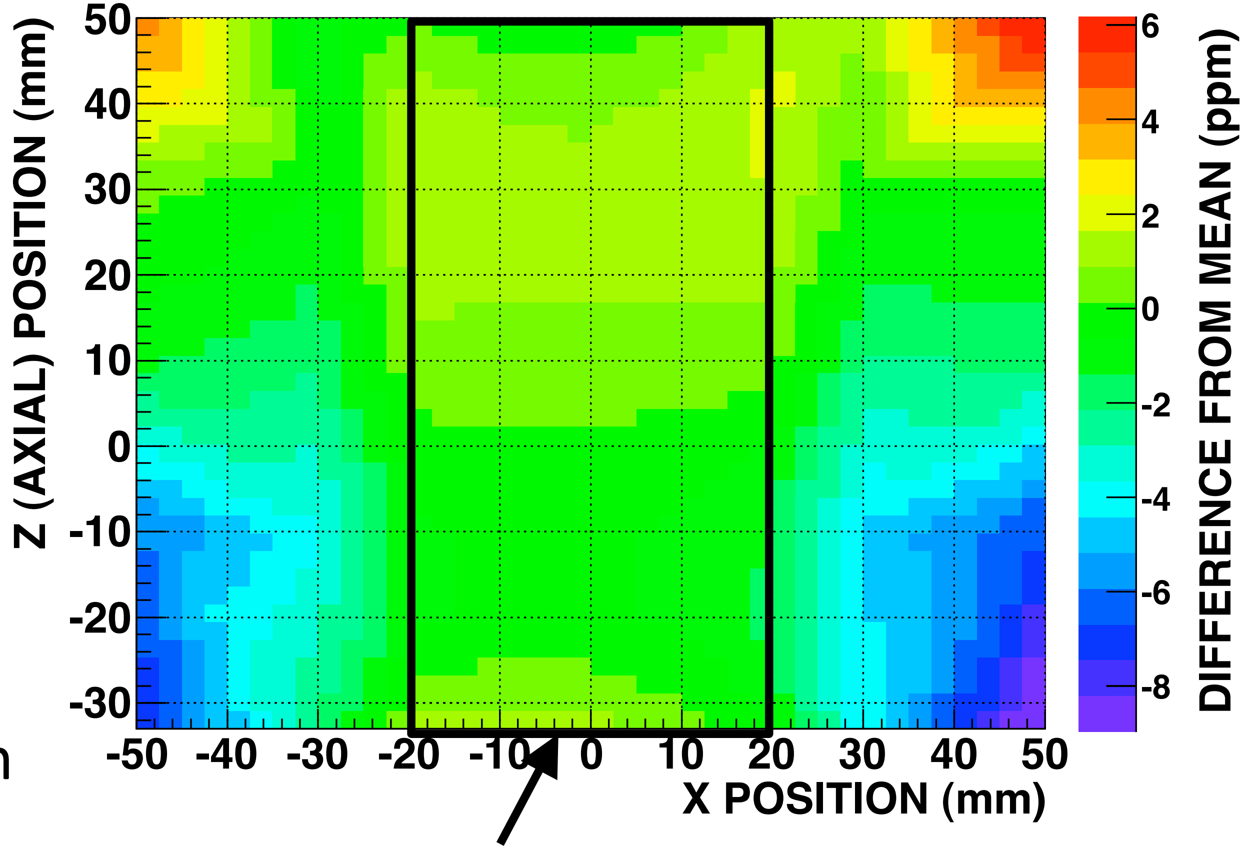
Prospects & Current status

- Magnetic Field: Compensation magnets
→ O(ppm) magnetic field uniformity (Done →)
- 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



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



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

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

→ It is installed in the final run setup.

Material Effect on Ps-HFS

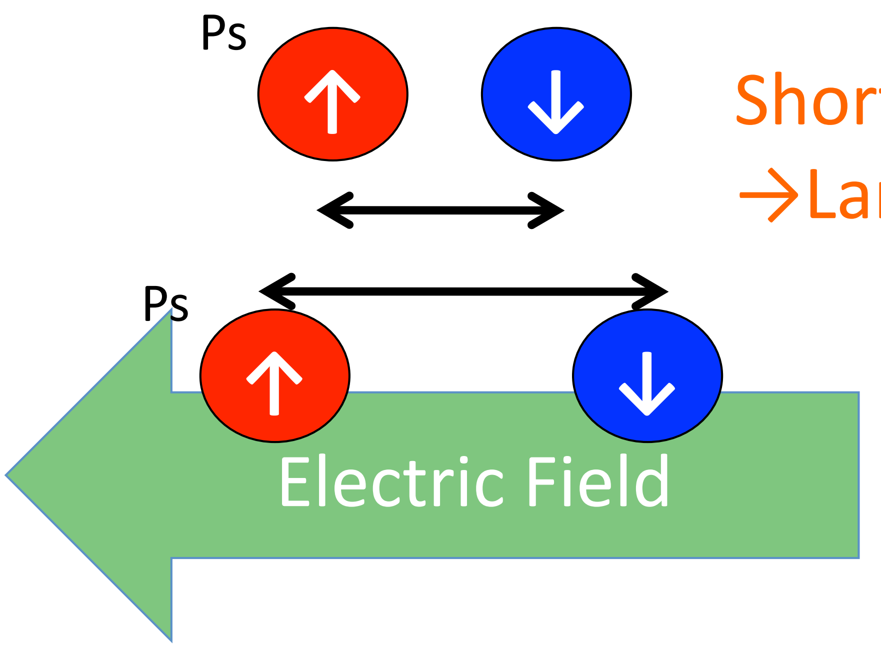
Spin-spin interaction between e^+ and e^-

→Depends on their distance

Electric field of surrounding materials

→Changes the distance of e^+ and e^- of Ps

→Shift of Ps-HFS (Stark Effect)



Short distance

→Large Ps-HFS

Long distance

→Spin interaction is small

→Small Ps-HFS

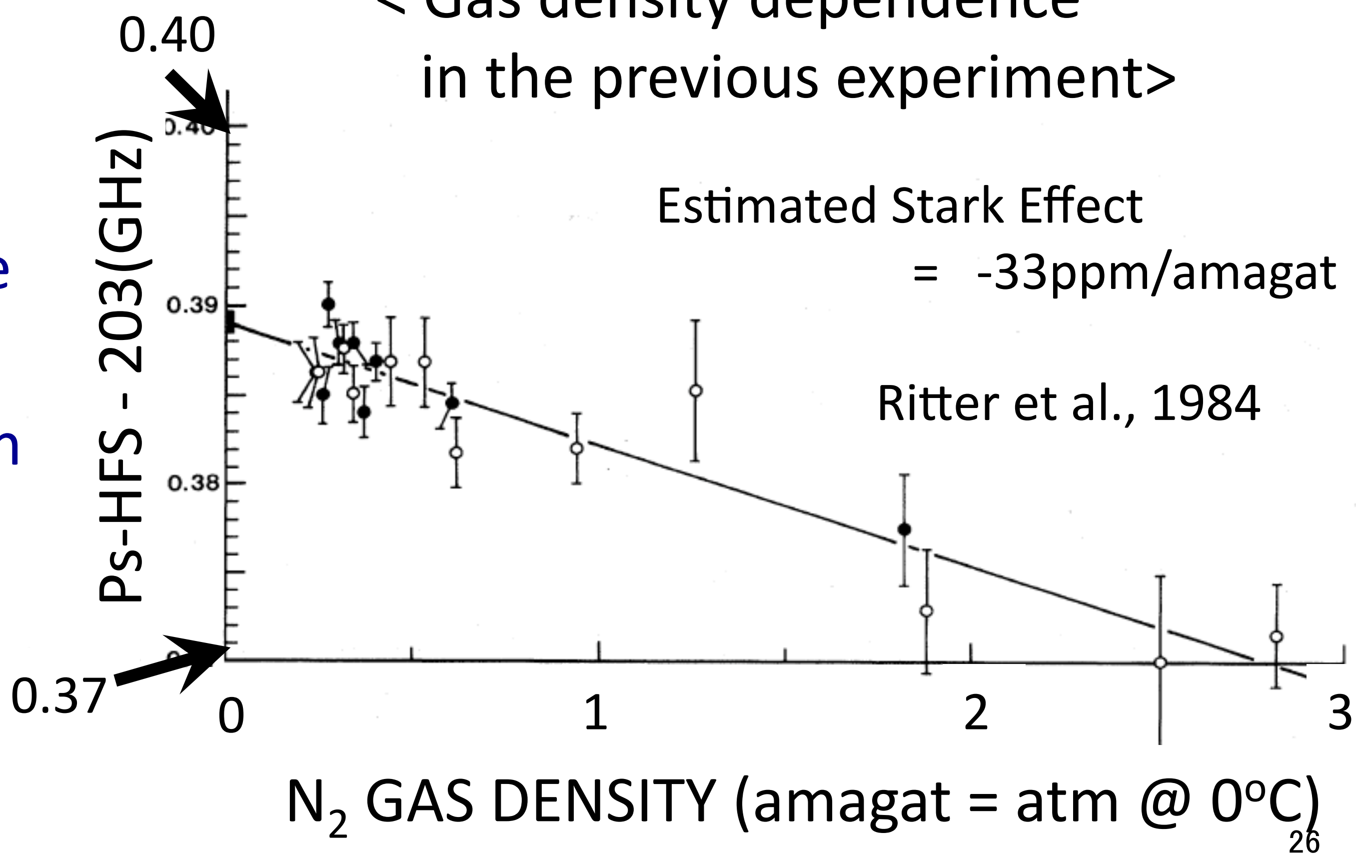
Material Effect Estimation in Previous Experiments

Stark Effect on Ps-HFS
∝Collision rate with materials
= (Material Density) × (Cross Section) x (Ps velocity)

→If the velocity of Ps is constant, the effect is just proportional to the material density.

→Linear extrapolation method is used in all the previous experiments with this assumption.

< Gas density dependence in the previous experiment>



Ps Thermalization Problem

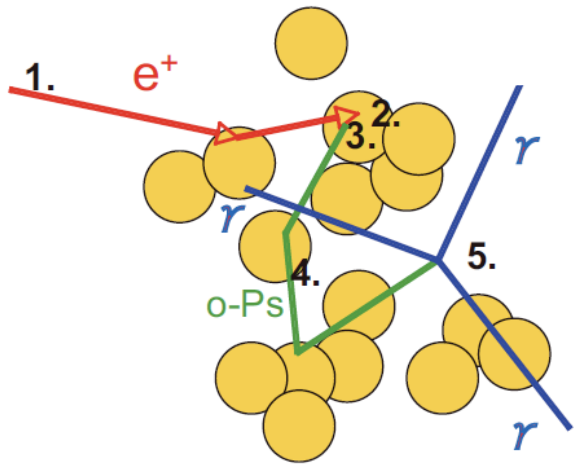
Formed o-Ps has a kinetic energy of about 1 eV.

o-Ps deposits its energy to the room temperature (1/30 eV) by collision with surrounding materials (the thermalization process).

If it takes much time to thermalize, the material effect ($\propto$ collision rate) **is not proportional to material density**.

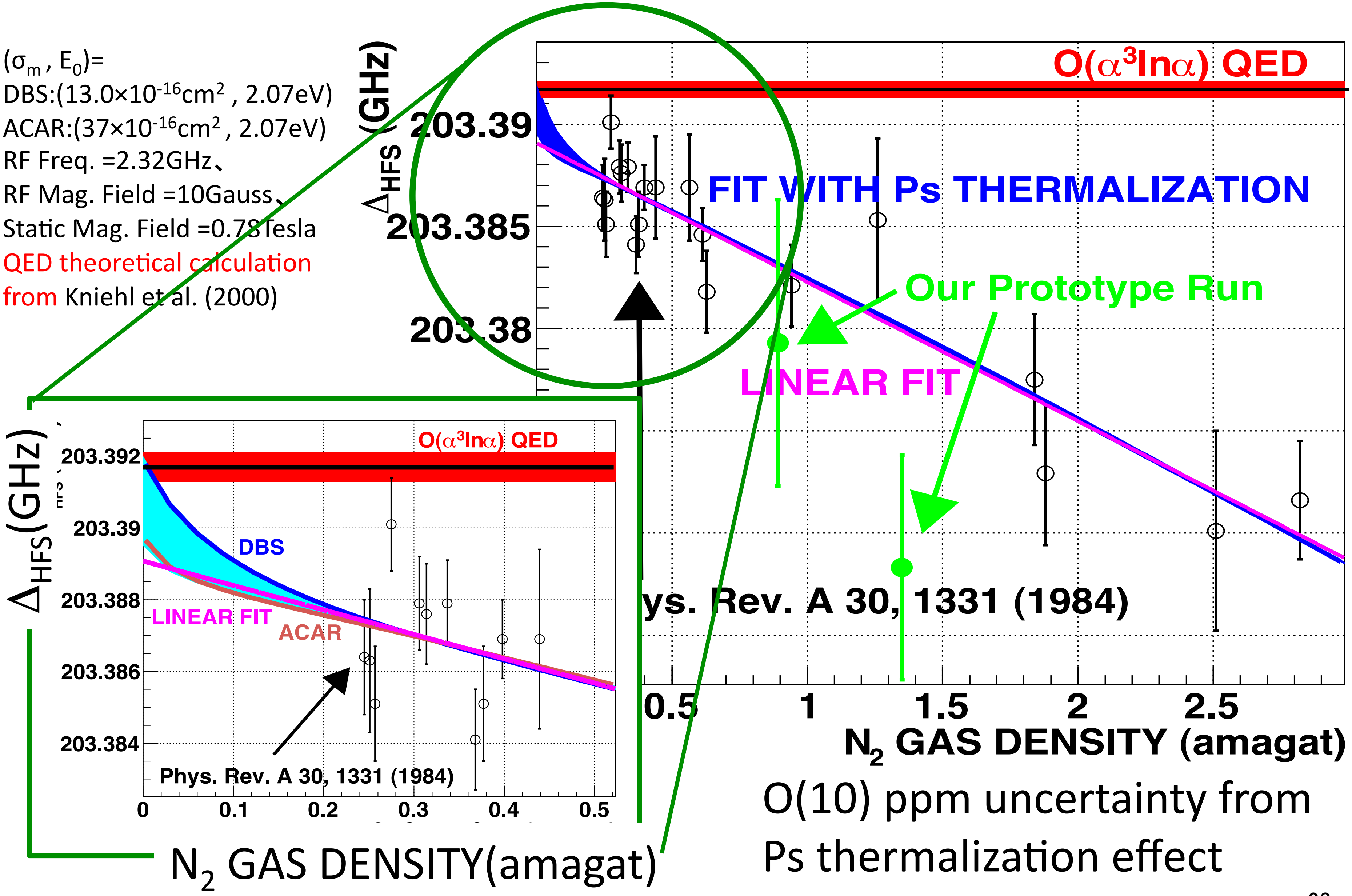
In fact, **it affects seriously** ("o-Ps lifetime puzzle" (1990's)).

→Ps thermalization effect can be a serious systematic error in Ps-HFS measurement.



Material Effect Estimation including Ps Thermalization Effect

(σ_m, E_0)=
DBS:(13.0×10^{-16}cm^2 , 2.07eV)
ACAR:(37×10^{-16}cm^2 , 2.07eV)
RF Freq. =2.32GHz、
RF Mag. Field =10Gauss、
Static Mag. Field =0.78Tesla
QED theoretical calculation from Kniehl et al. (2000)

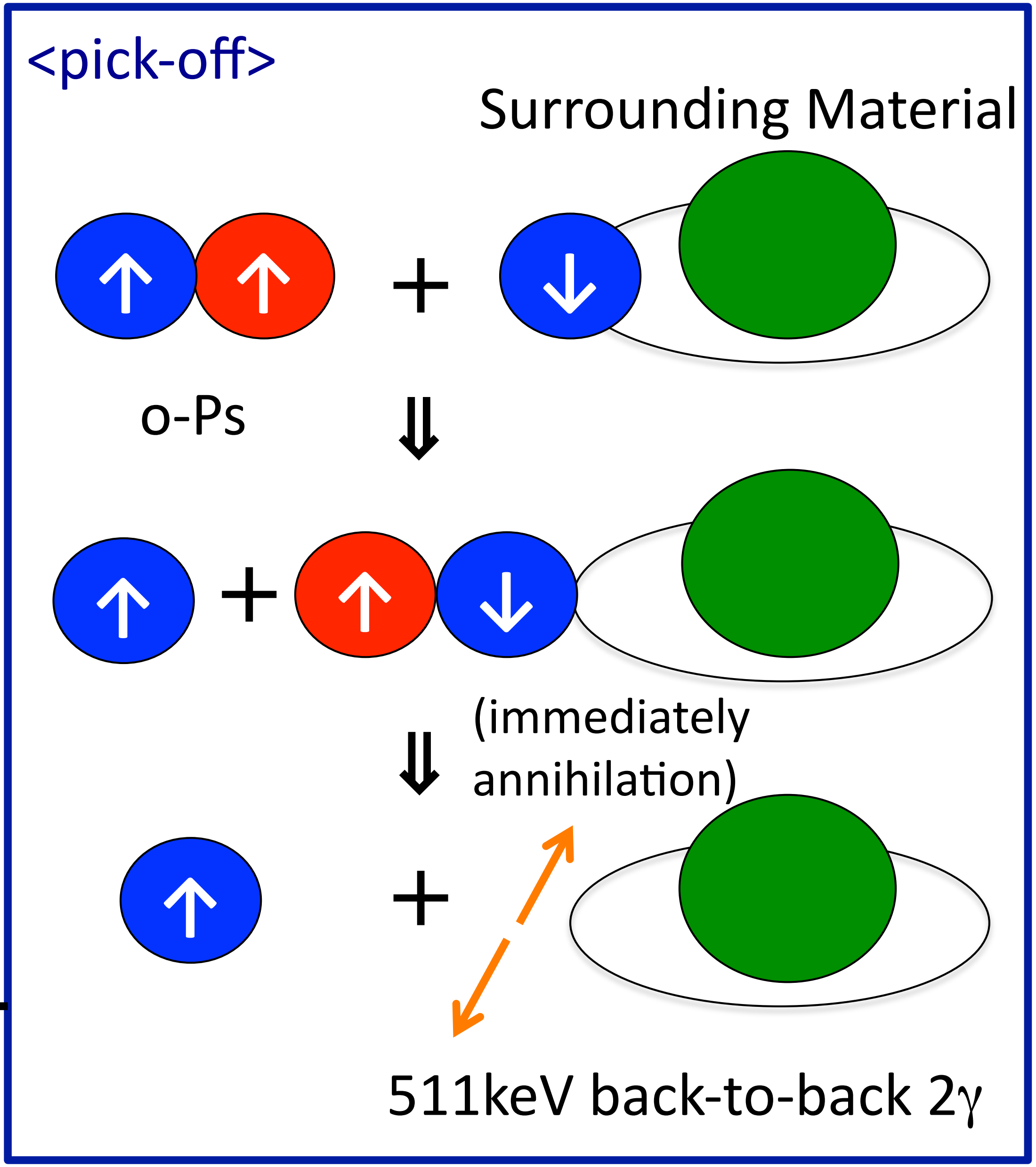


O(10) ppm uncertainty from Ps thermalization effect

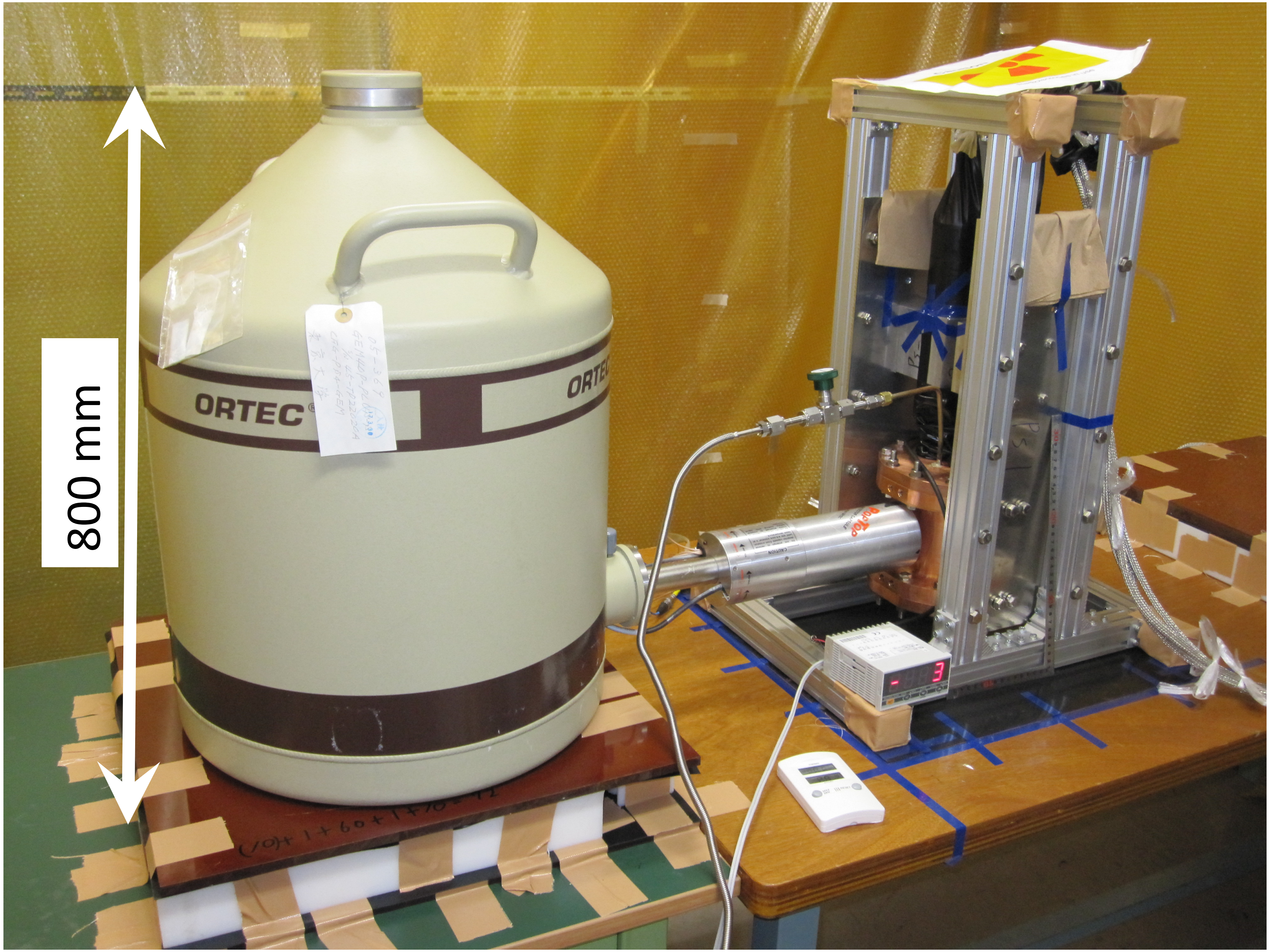
How to Measure Ps thermalization?

- Use o-Ps' pick-off 2γ annihilation
- pick-off (t)
  ∝ cross section of collision (σ)
  × material density
  × o-Ps amount (t)
  × v(t)

$$\sigma \cdot v(t) \propto \frac{\textbf{pick-off (2}\gamma\textbf{ decay)}}{\textbf{o-Ps (3}\gamma\textbf{ decay)}}$$

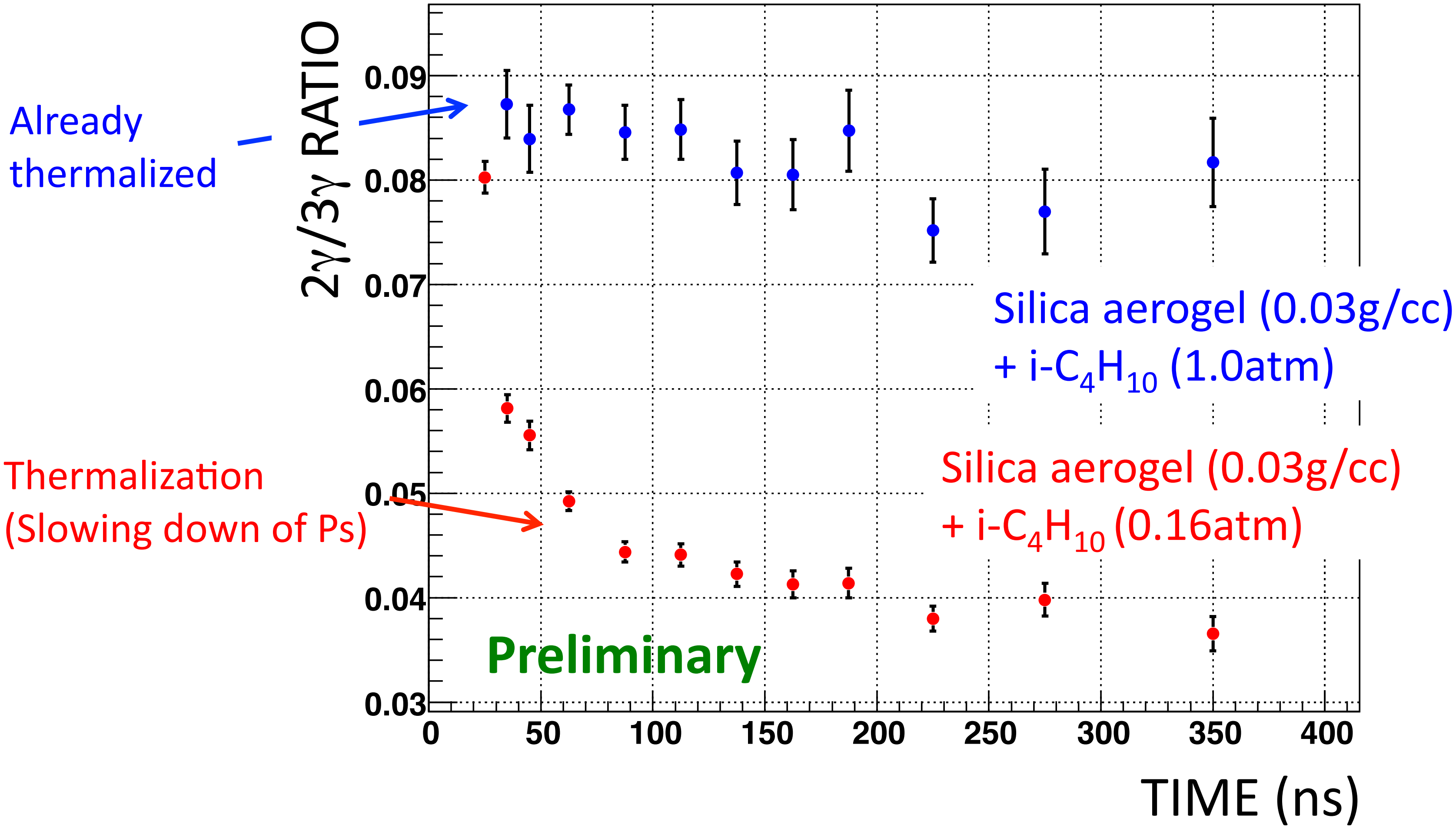


Measurement of Ps Thermalization
Experimental Setup



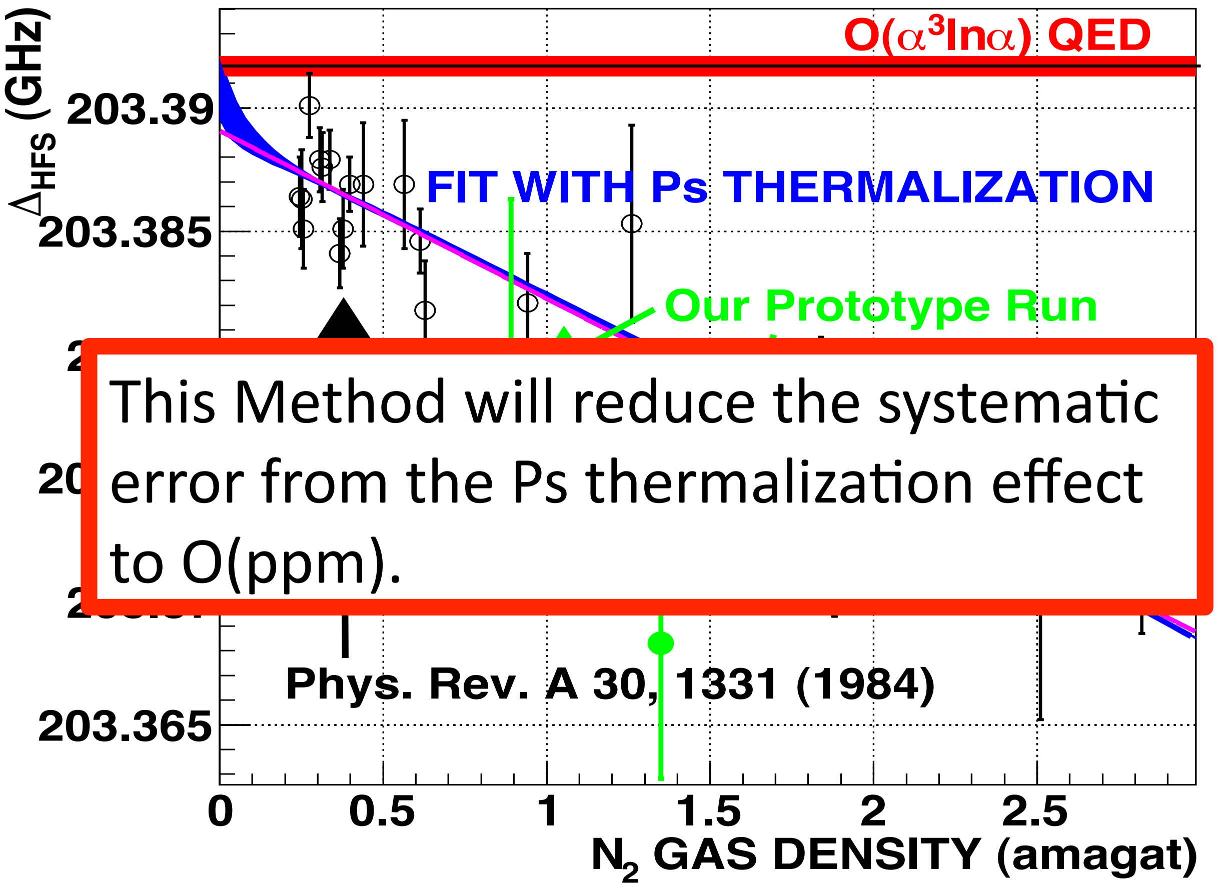
$2\gamma/3\gamma$ Ratio

- $2\gamma/3\gamma$ ratio is obtained by 1-month run
- The more i-C_4H_{10} pressure, the faster the Ps thermalization



Method of Material Effect Correction to Our Data

1. Measure the Ps thermalization parameters precisely.
2. Fit the obtained HFS data with nonlinear function including Ps thermalization effect (in the final run).



This Method will reduce the systematic error from the Ps thermalization effect to O(ppm).

Conclusion of my part

- There is a 3.9 σ discrepancy in the ground state Ps-HFS between the experimental results and the QED prediction.
- The prototype run has been performed.
- Our new experimental setup uses 3 new methods.
  1. Superconducting magnet (→Good uniformity of magnetic field in large volume)
  2. β-tagging system and Timing information (→Correct treatment of Ps thermalization effect)
  3. High performance γ-ray detectors (→High statistics)
- 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.

Backup

Members (Indirect Measurement)

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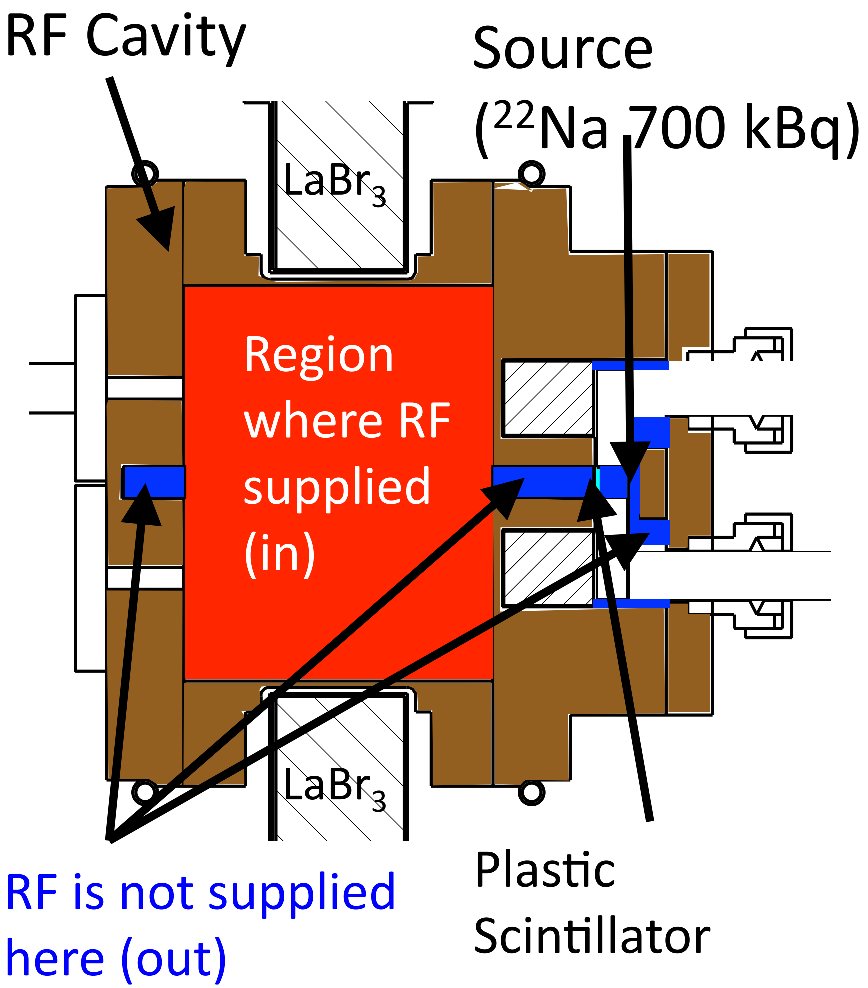
Fitting the Energy Spectra



・There is a region where RF is supplied and a region where RF is not supplied.

・Ps can be formed and decay in both region.

・When RF is OFF, 2γ/3γ decay ratio does not depend on the region.

OFF Spectrum

Normalized by livetime.

$$S_{OFF} = \underbrace{A_{OFF}\left(S_{3\gamma MC,out} + \beta S_{2\gamma MC,out}\right)}_{\text{Region without RF}} + \underbrace{A_{OFF}\left(S_{3\gamma MC,in} + \beta S_{2\gamma MC,in}\right)}_{\text{Region with RF}}$$

・When RF is ON, 2γ/3γ decay ratio changes only in the “in” region.

ON Spectrum

$$S_{ON} = \underbrace{A_{OFF}\left(S_{3\gamma MC,out} + \beta S_{2\gamma MC,out}\right)}_{\text{Region without RF}} + \underbrace{A_{ON}\left(S_{3\gamma MC,in} + \Gamma S_{2\gamma MC,in}\right)}_{\text{Region with RF}}$$

A_{OFF} , A_{ON} 3γ decay prob.

β , Γ 2γ/3γ decay ratio

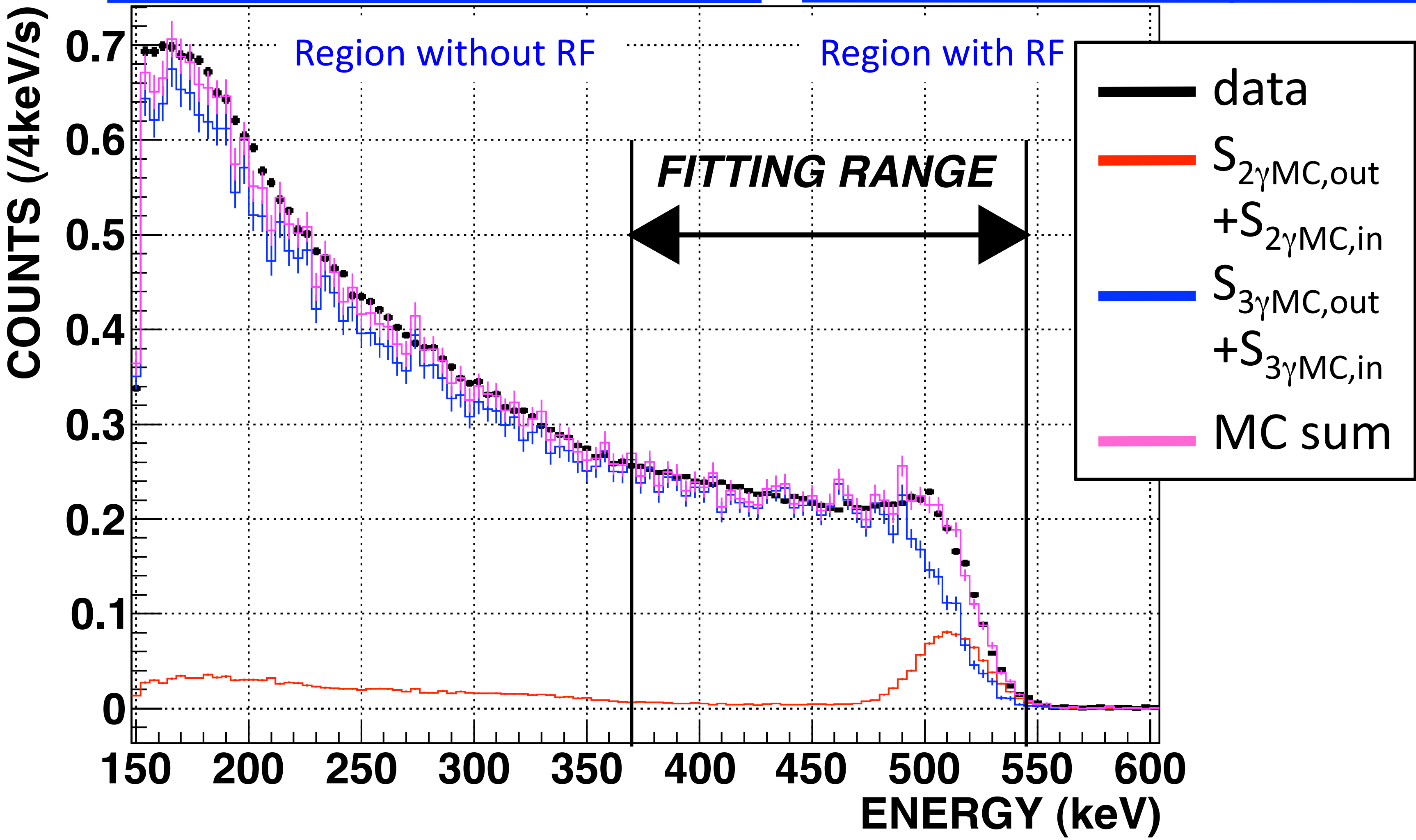
$S_{3\gamma MC}$, $S_{2\gamma MC}$ MC spectra

Fitting the Energy Spectrum by Monte Carlo Simulation (RF-OFF)

$$S_{OFF} = A_{OFF}\left(S_{3\gamma MC,out} + \beta S_{2\gamma MC,out}\right) + A_{OFF}\left(S_{3\gamma MC,in} + \beta S_{2\gamma MC,in}\right)$$

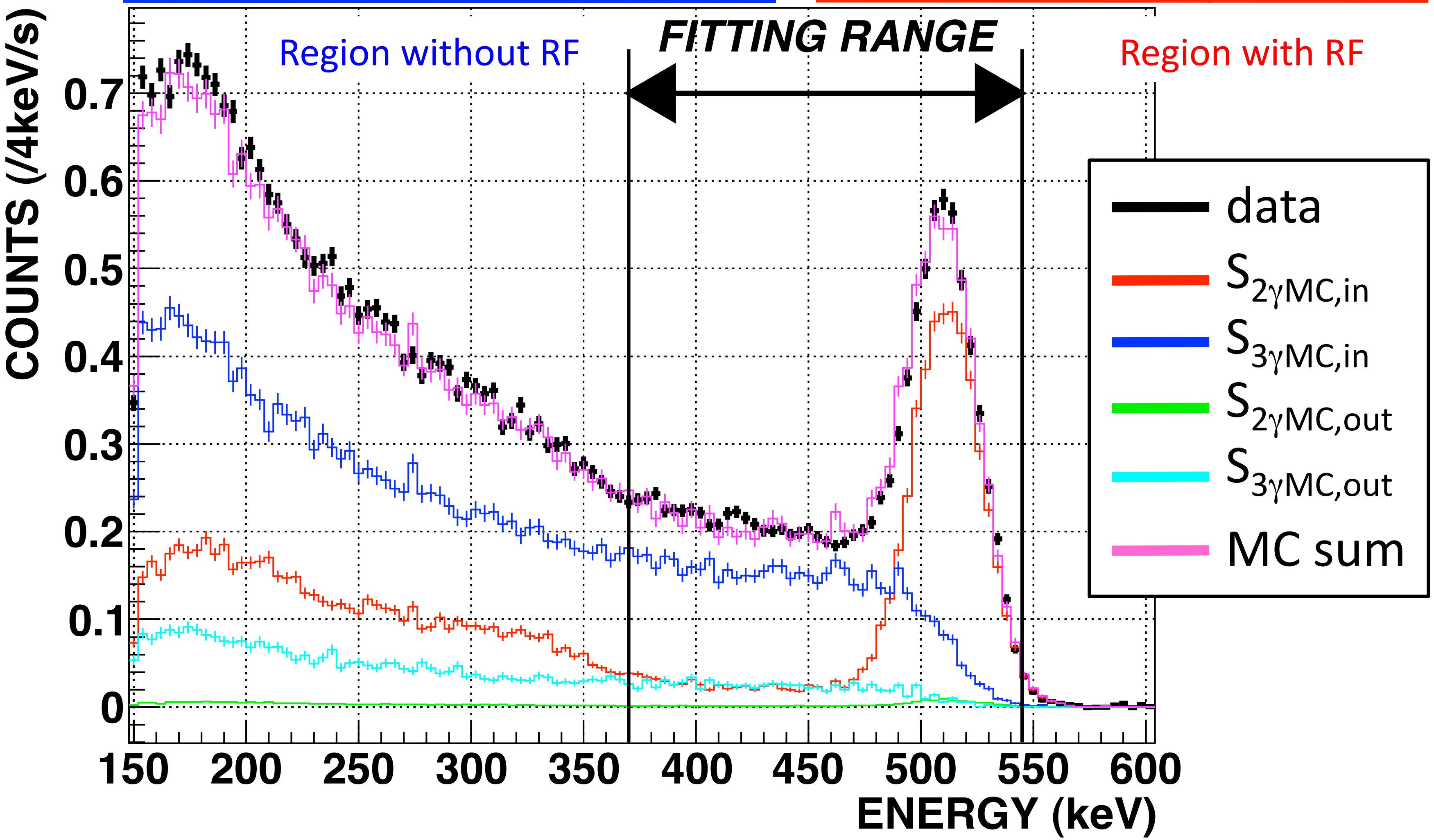
Region without RF

Region with RF

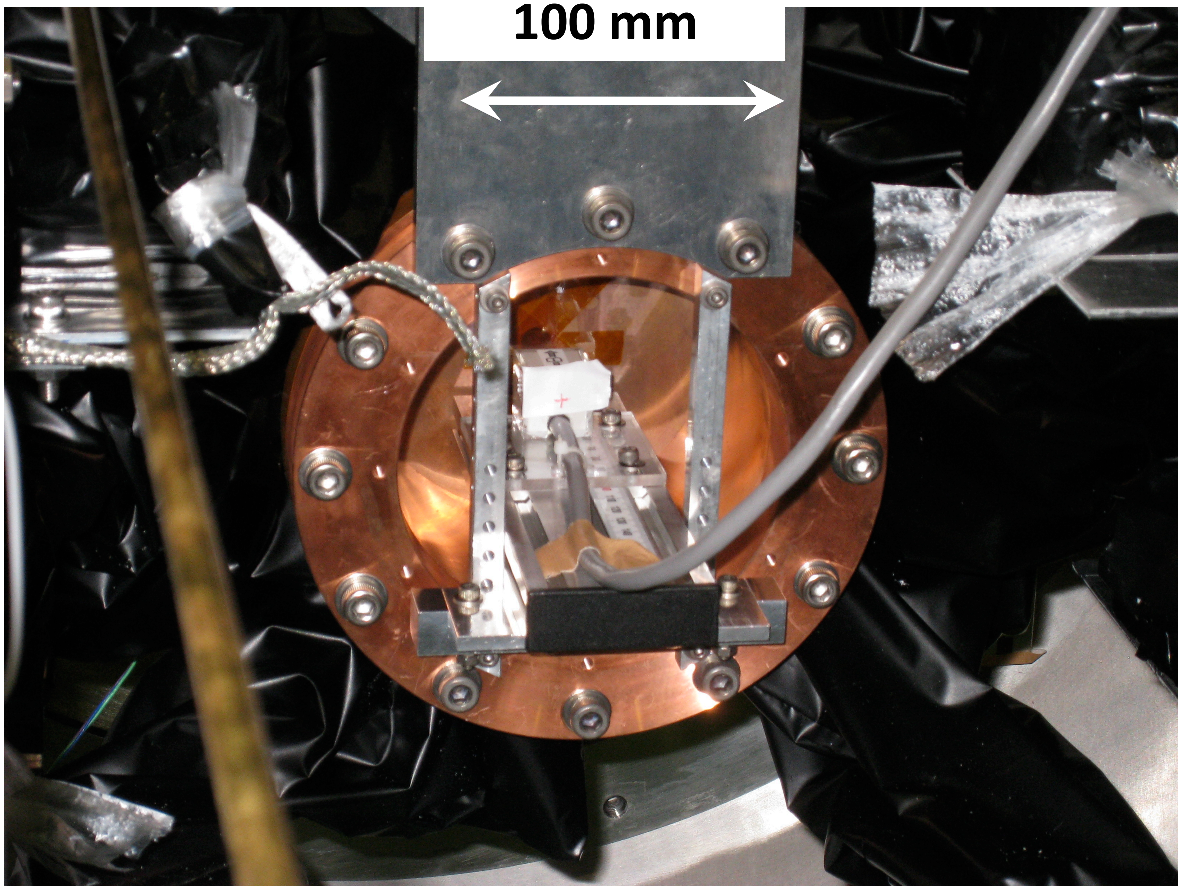


Fitting the Energy Spectrum by Monte Carlo Simulation (RF-ON)

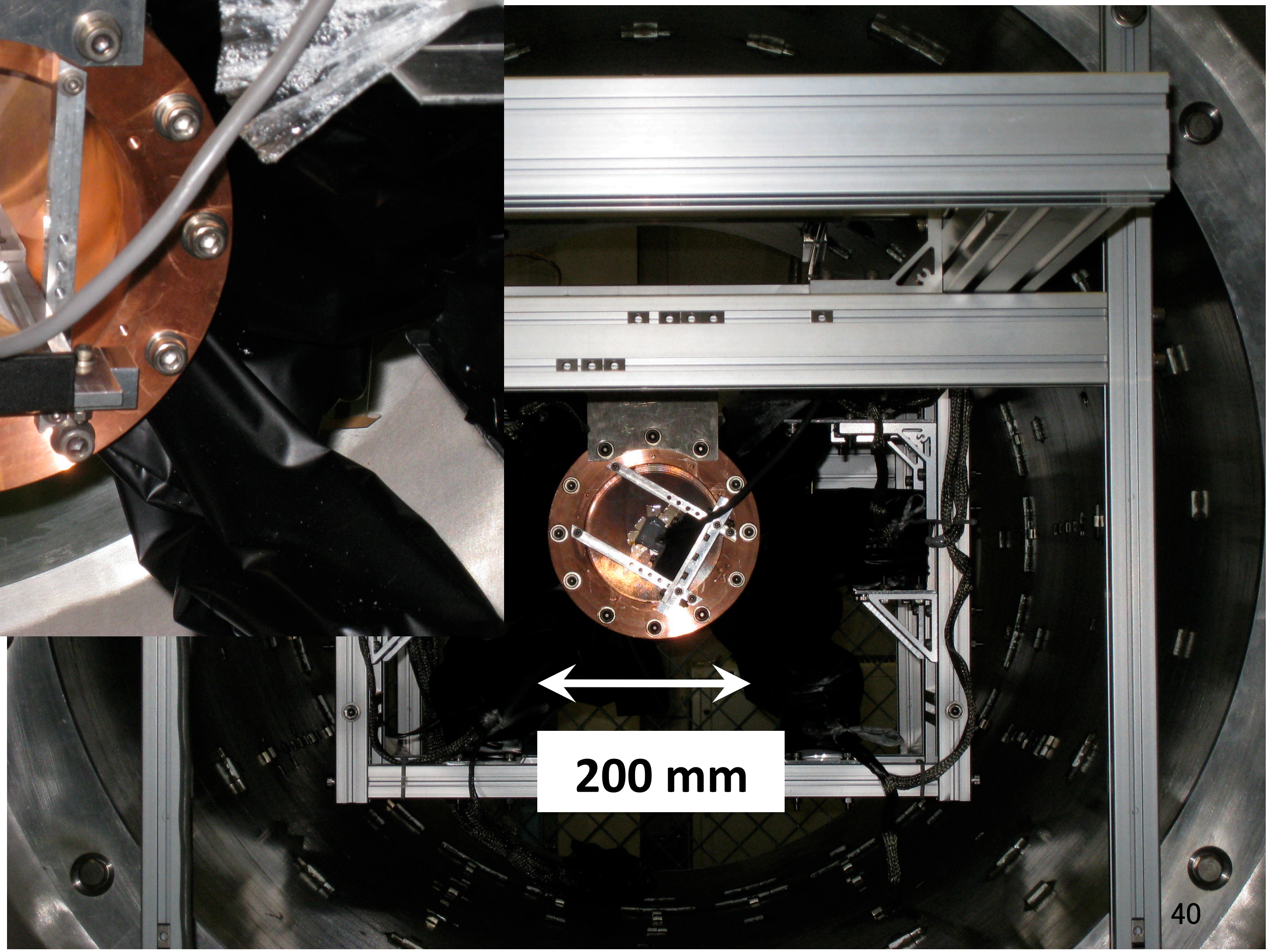
$$S_{ON} = A_{OFF}\left(S_{3\gamma MC,out} + \beta S_{2\gamma MC,out}\right) + A_{ON}\left(S_{3\gamma MC,in} + \Gamma S_{2\gamma MC,in}\right)$$



Magnetic Field Measurement

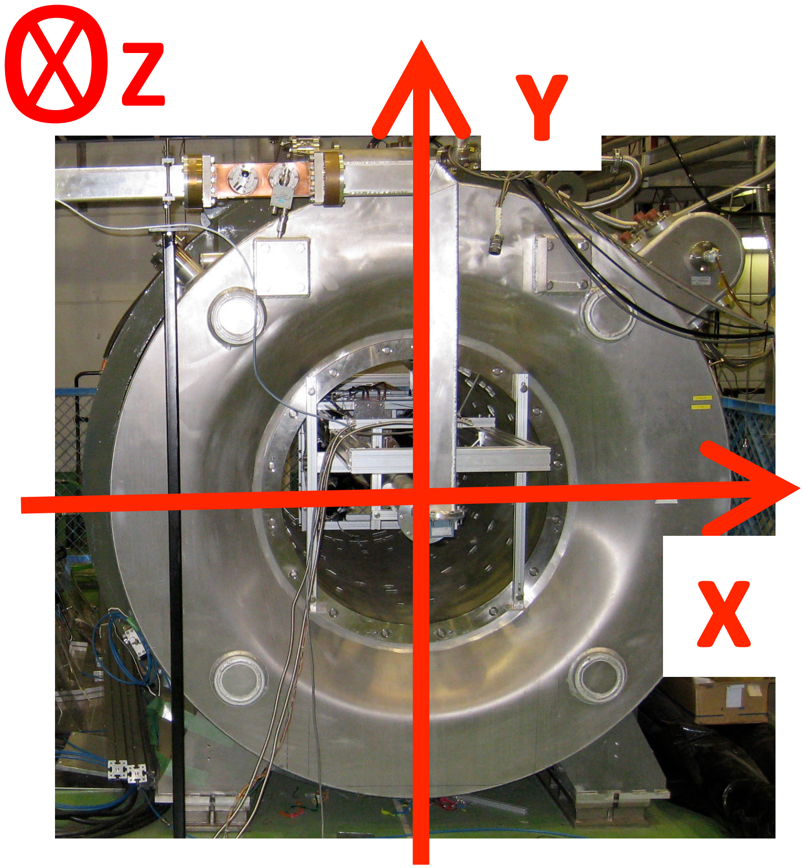


Measured the magnetic field at 310 points in the RF cavity using NMR probe.

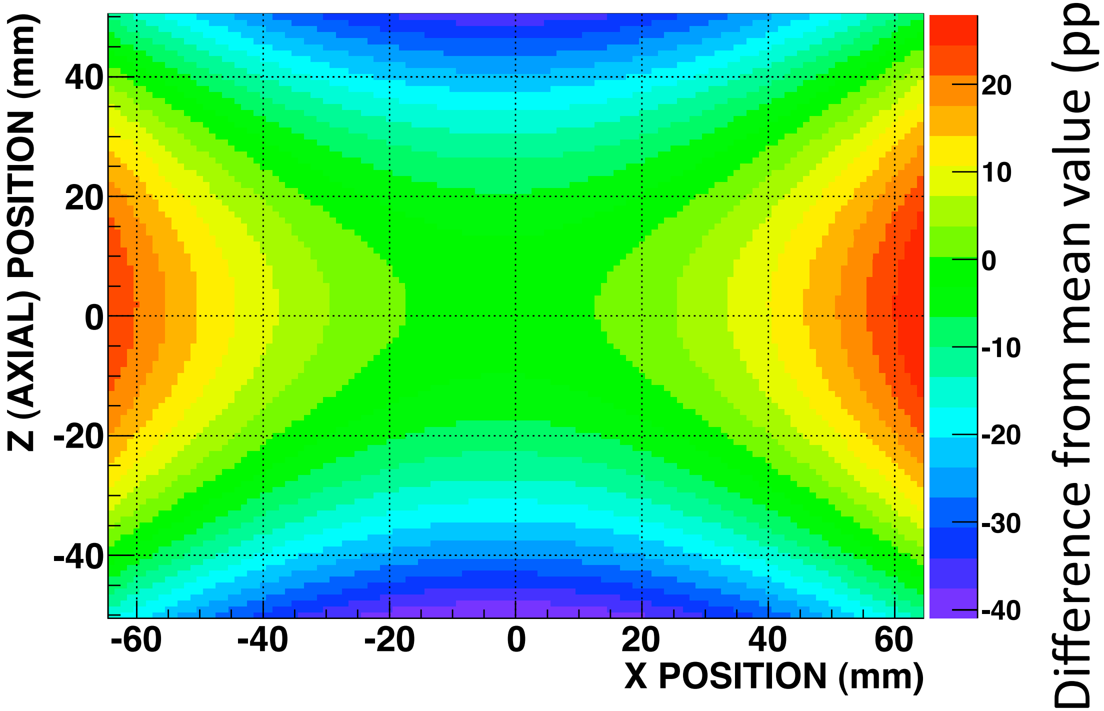


Made the map of the magnetic field.

Non-Uniformity of the Magnetic Field



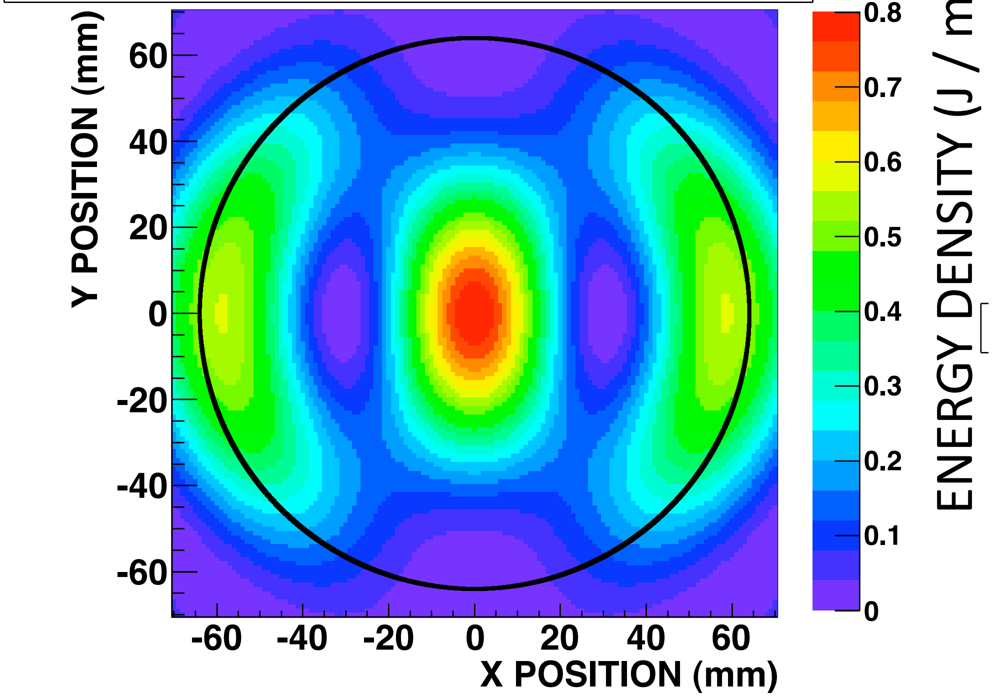
Magnetic field distribution on Y=0 plane. (O is the center of the cavity)



- Non-uniformity of the magnetic field is serious systematic uncertainty.
- Non-uniformity in the RF cavity is 23.1 ppm (RMS).

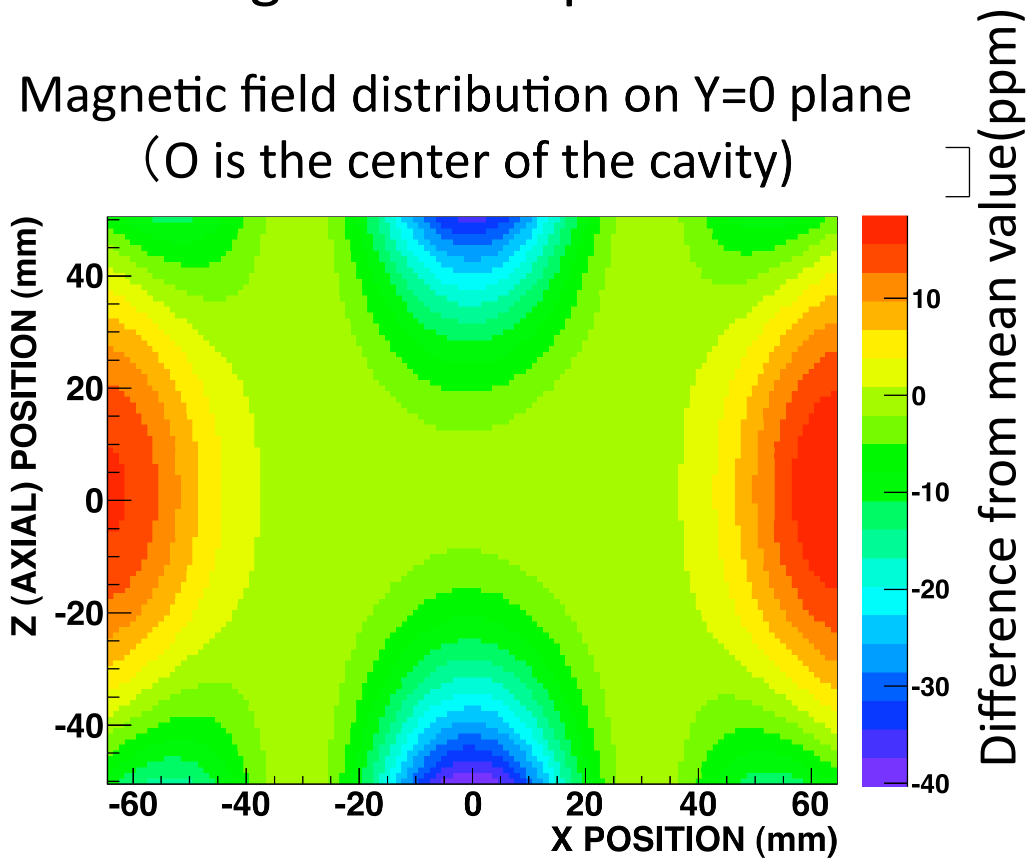
Weight 1. RF Power distribution

Energy distribution of RF magnetic field
(TM$_{110}$ mode)



After weighting the RF magnetic field power

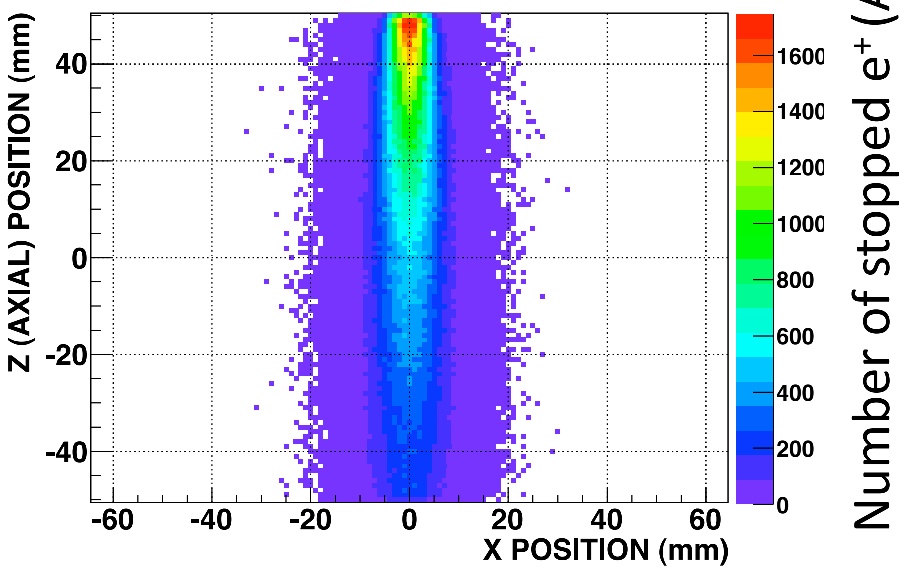
Magnetic field distribution on Y=0 plane
（O is the center of the cavity)



Uniformity gets better to
14.2 ppm (RMS)

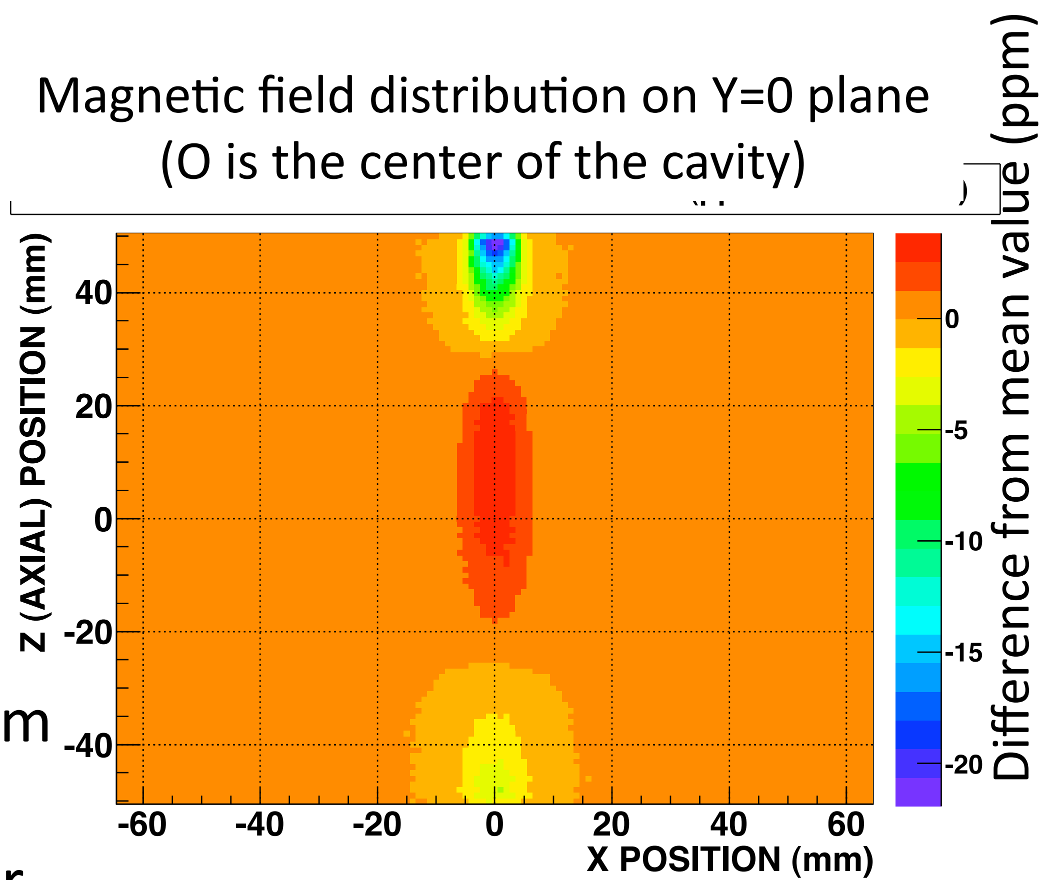
Weight 2. Positron Stop Position

e^+ stop position distribution
(Geant4 MC simulation)



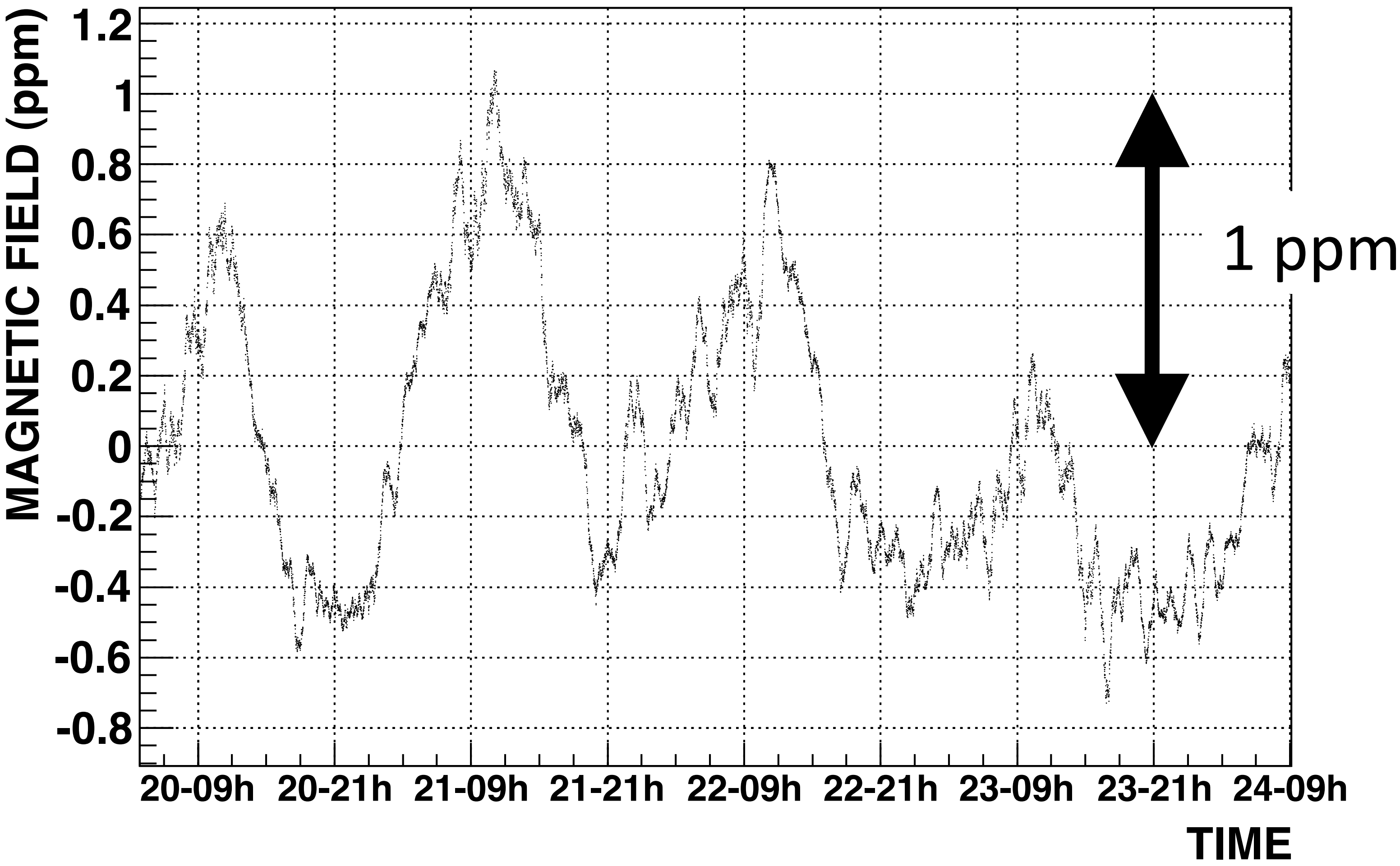
After applying the RF power and e^+ stop position weight

Magnetic field distribution on Y=0 plane
(O is the center of the cavity)

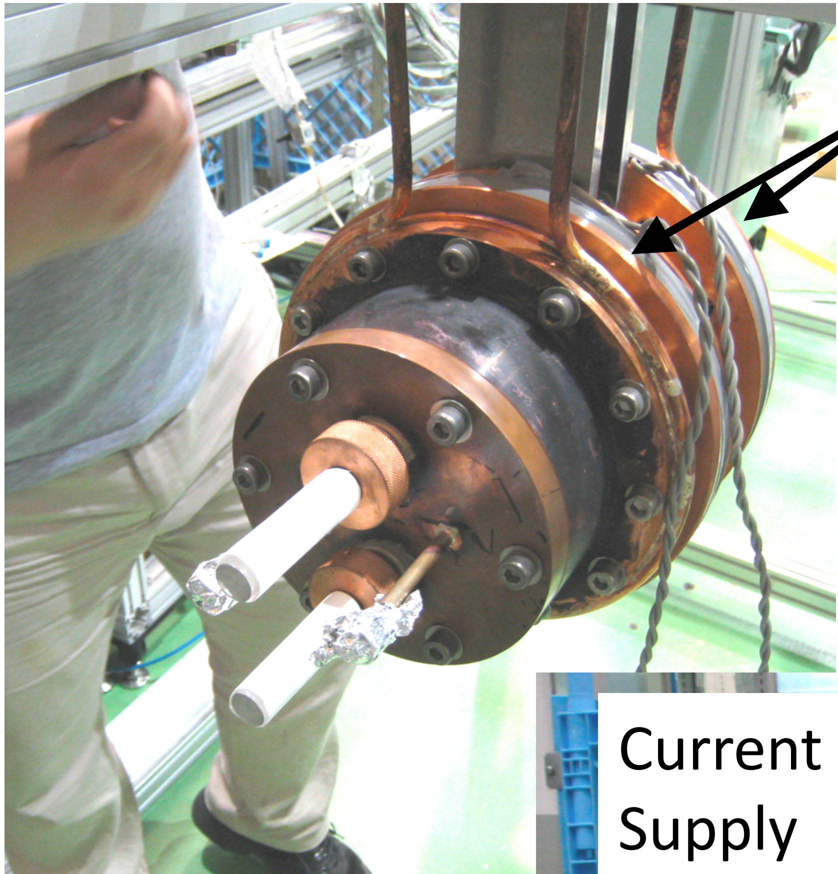


Uniformity gets better to 10.4 ppm (RMS) (21 ppm in HFS)
→This is the final systematic error.

Stability of the magnetic field



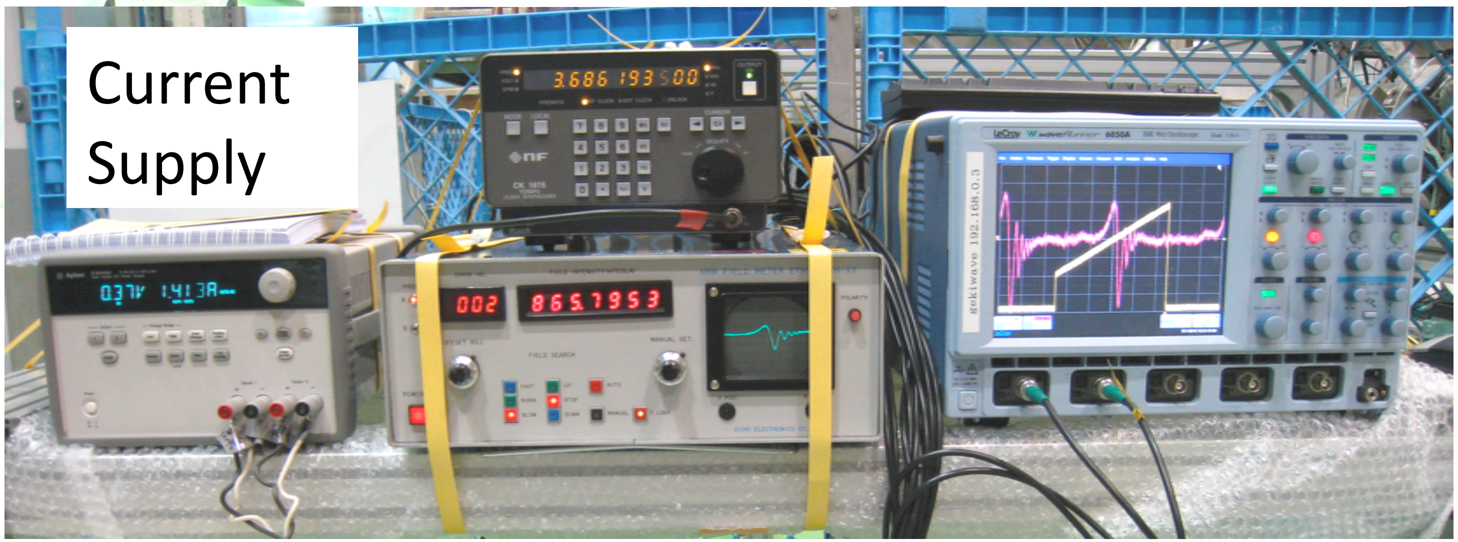
Compensation Magnet



2 ring coils

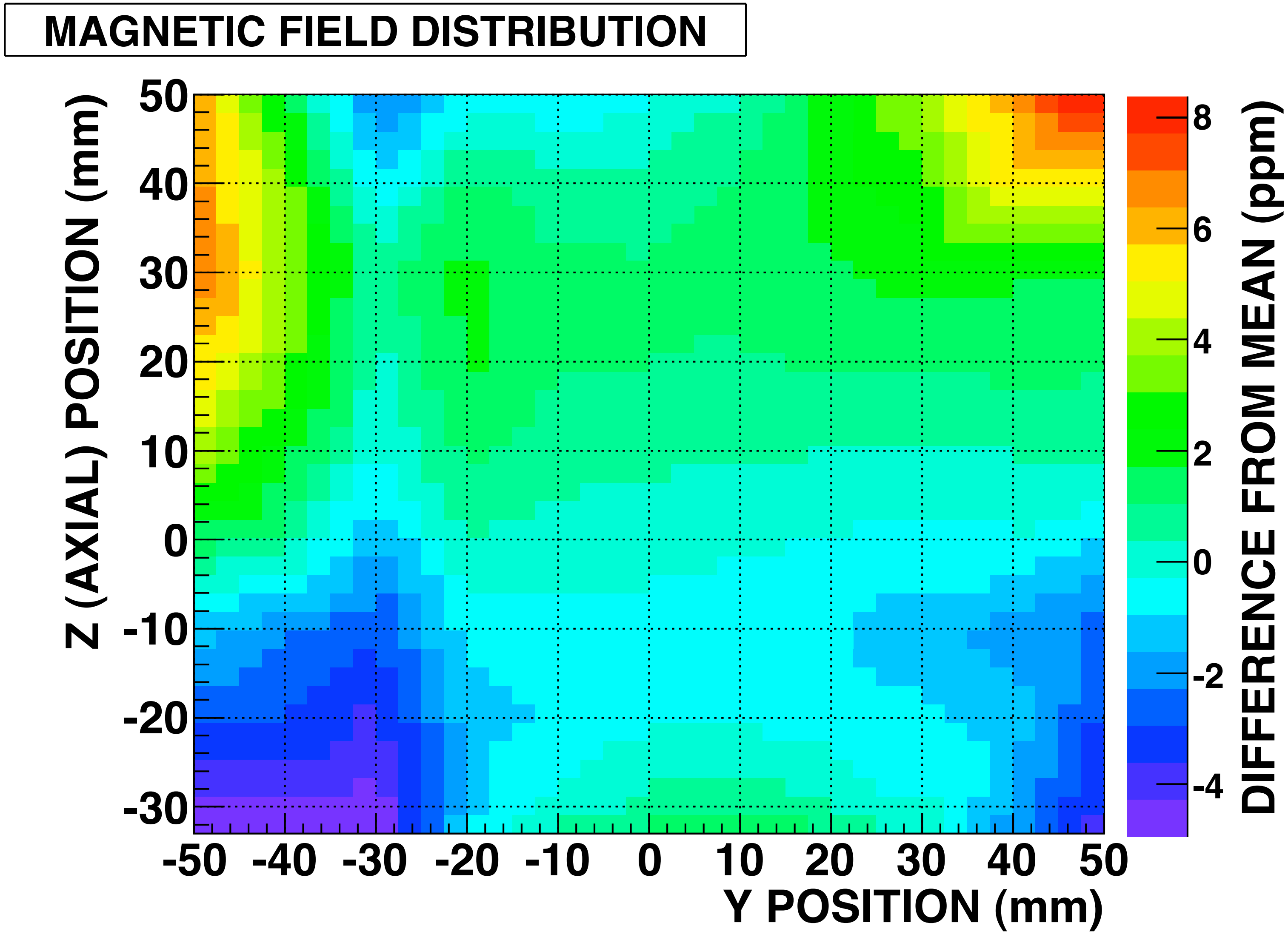
Clock
Generator &
NMR
Magnetometer

Oscilloscope



Current
Supply

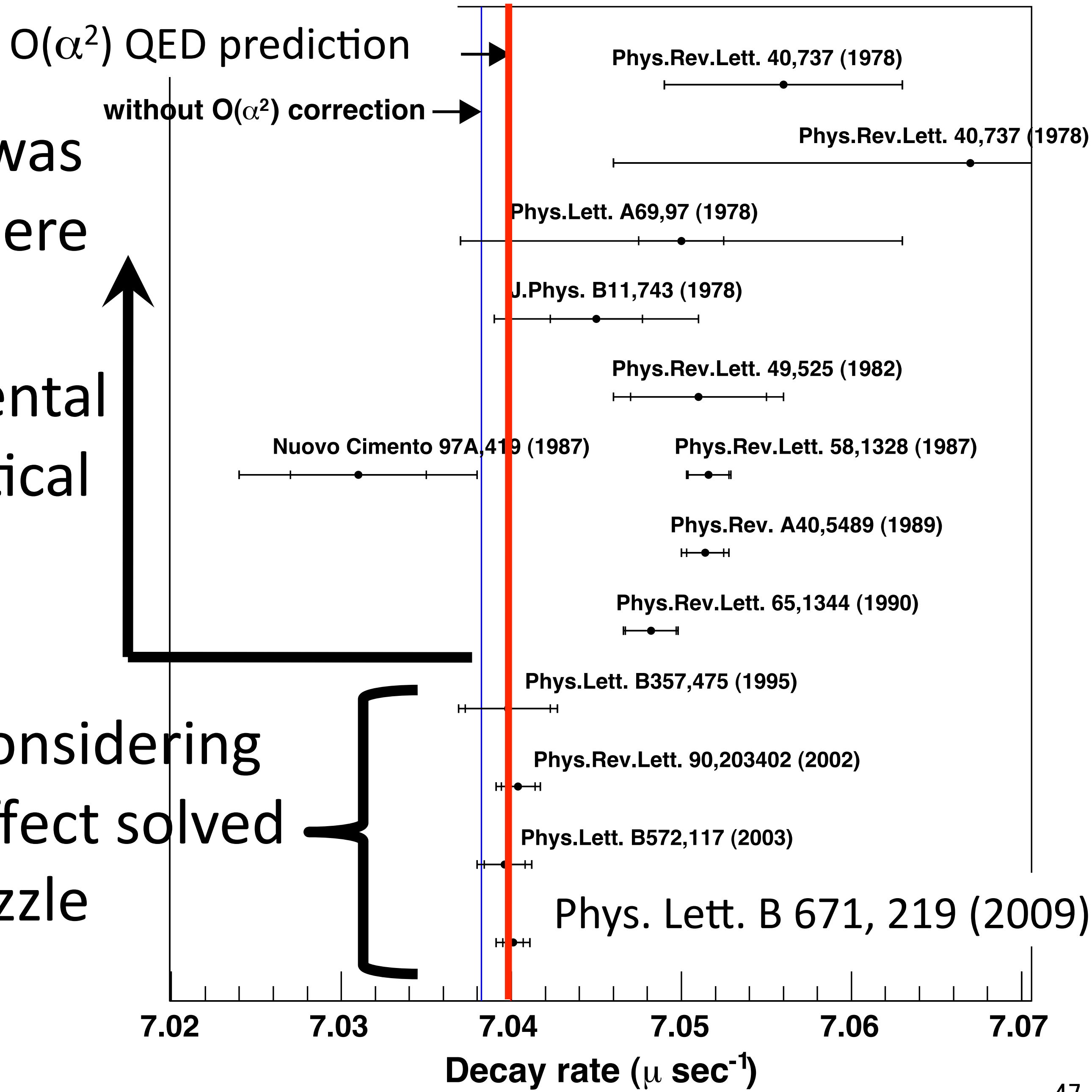
Compensation Magnet



Solution to o-Ps lifetime puzzle

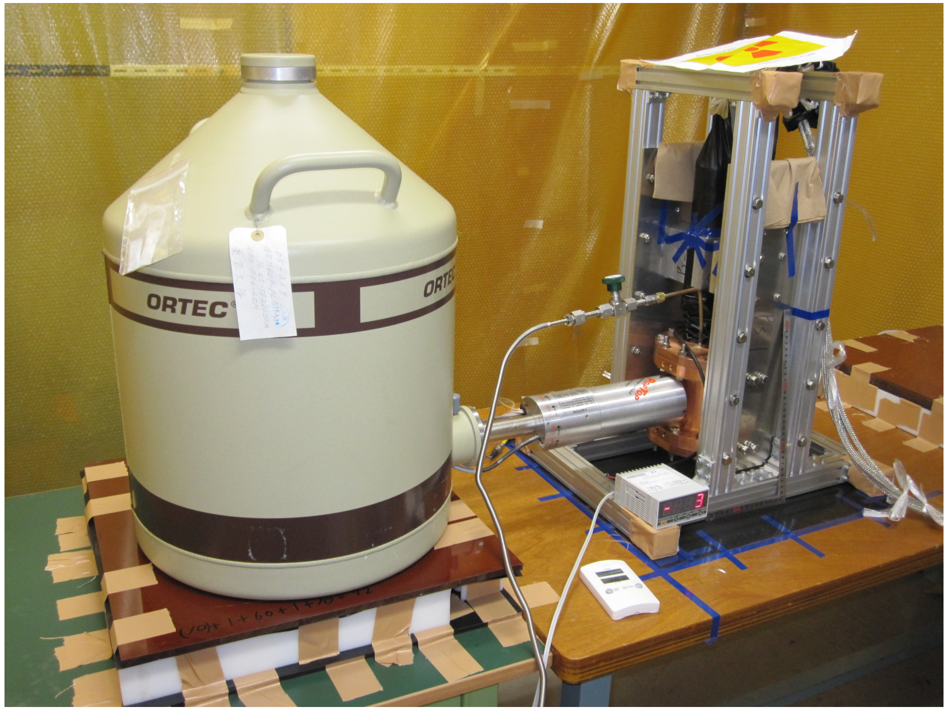
Ps thermalization was not considered. There was a discrepancy between experimental values and theoretical calculation.

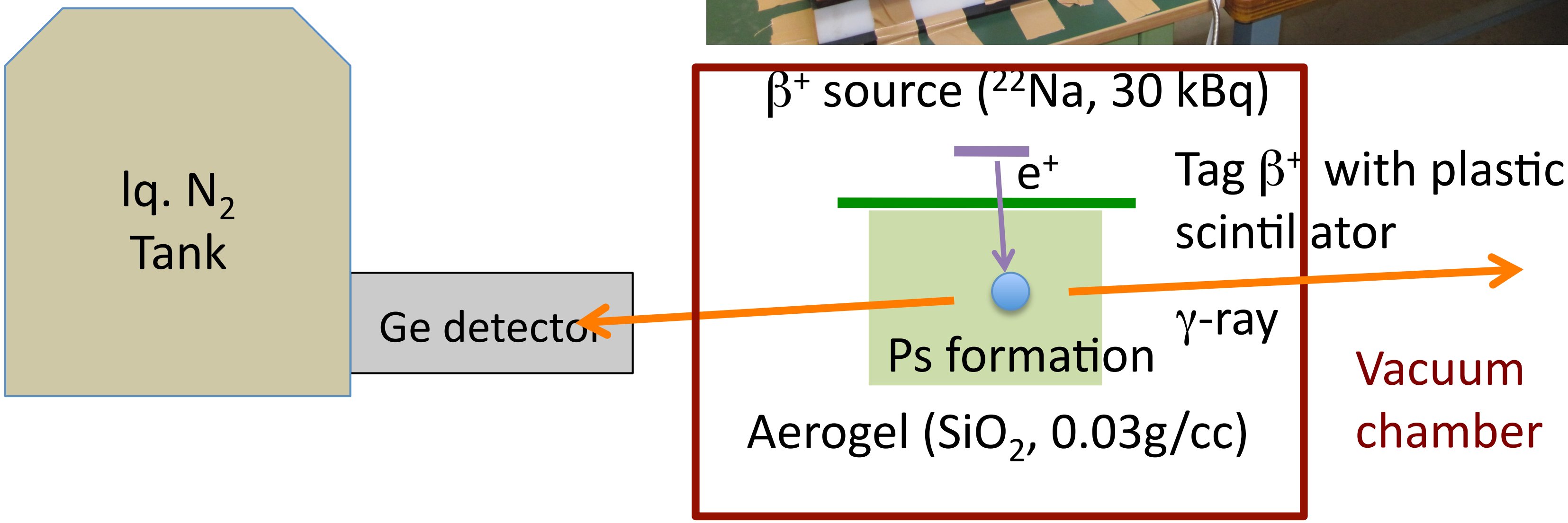
New experiments considering Ps thermalization effect solved the o-Ps lifetime puzzle



Measurement of Ps Thermalization Experimental Setup (Overall)

- Timing; START by Plastic Scintillator & STOP by Ge detector
- Stop e^+ in Silica aerogel and form Ps
- Source is inside the vacuum chamber.
- Change thermalization condition by changing the gas and its pressures.

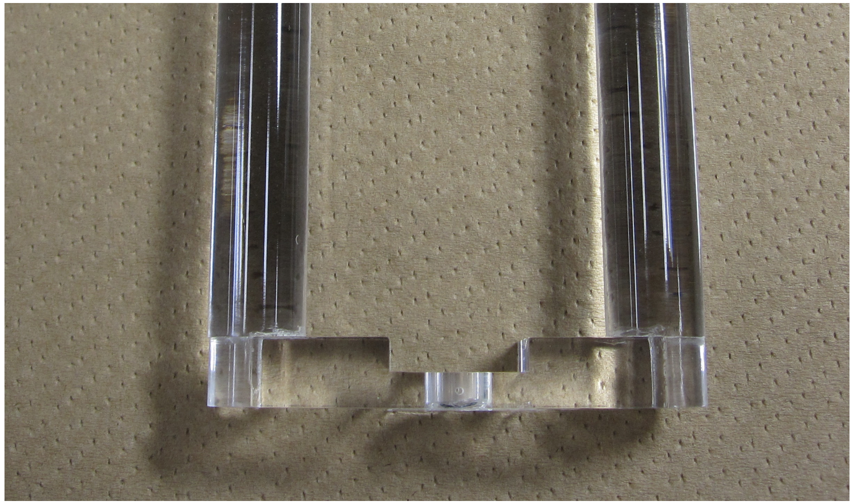


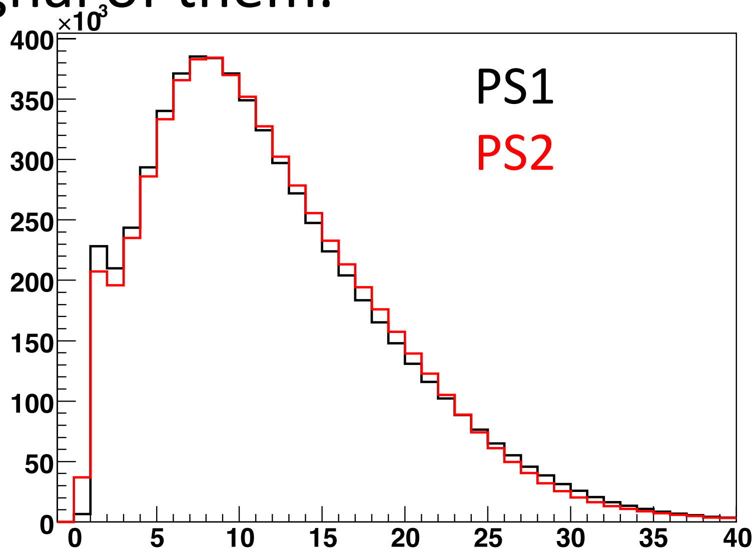


Ps Thermalization Experimental Setup (β^+-System)

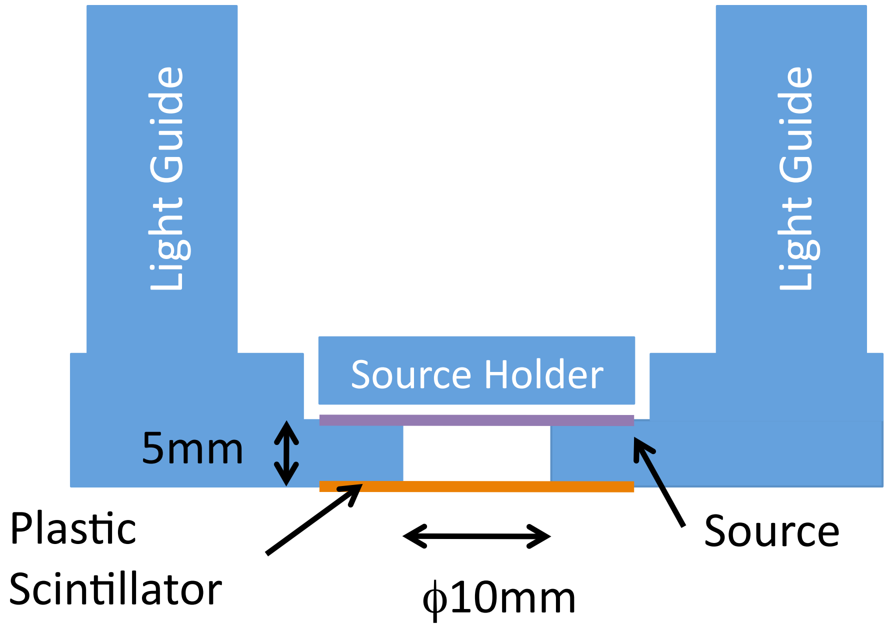
- Source : ^{22}Na (30kBq、Ti foiled)
- β^+ : Detect by Plastic Scintillator (200μm thick)
- The scintillation lights are guided through light guides into two R329s.

→START is made by coincidence signal of them.





Plastic Scintillator Energy (P.E.)



Ps Thermalization Experimental Setup (Aerogel, Vacuum Chamber)

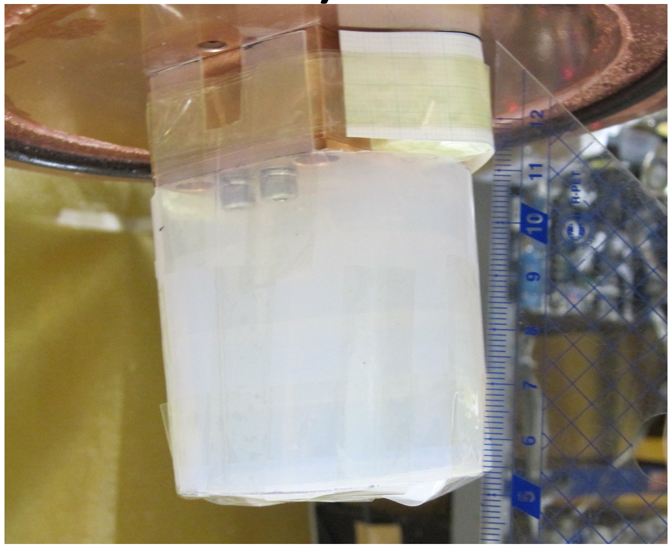
- Silica Aerogel：0.03g/cc

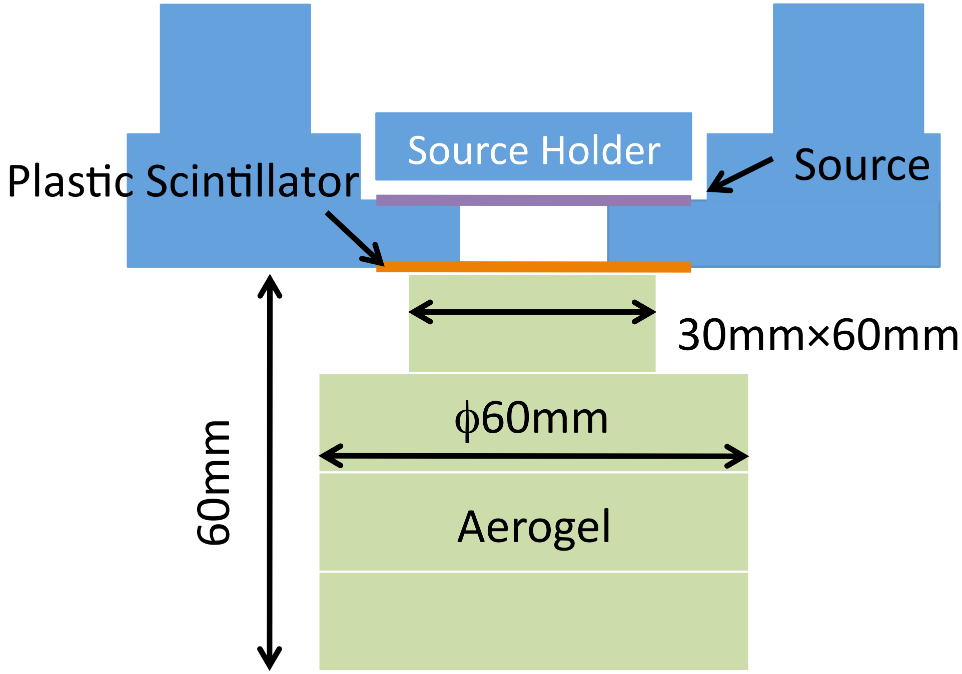
（High Ps formation fraction.

Effect from aerogel is measured independently.）

- Vacuum Chamber：Oxgen-free Copper

ϕ130mm×100mm×t1.5mm



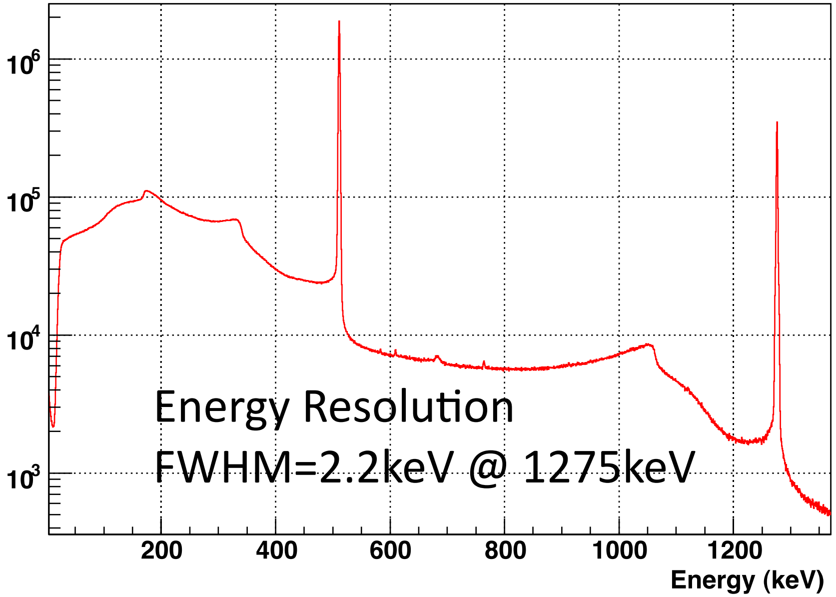


Ps Thermalization Experimental Setup (γ-ray Detector)

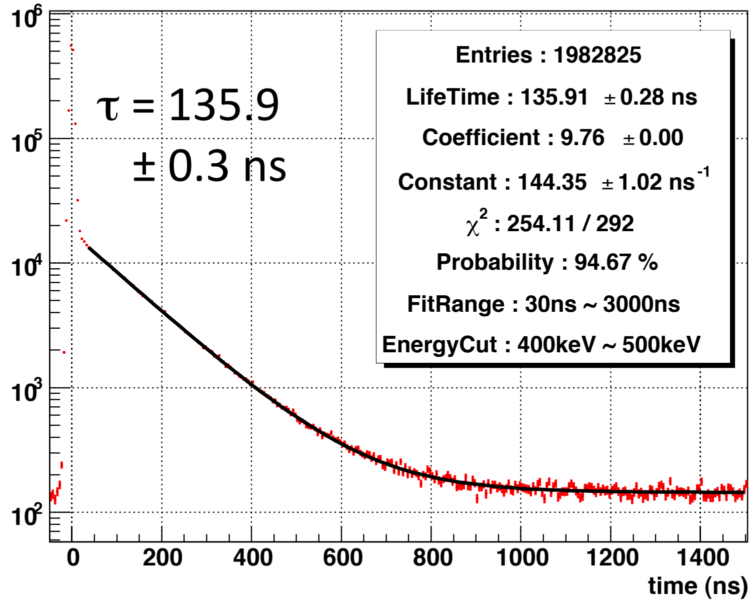
- Ge detectors (Ortec GEM 38195-P-plus series)
- Timing Correction is performed by cutting the slow components using triple threshold.

< Measurement with Silica aerogel (0.03 g/cc) + i-C_4H_{10} (0.16 atm) >

Energy Histogram



Timing Histogram (after correction)



Estimation of o-Ps and pick-off annihilation

1, Make energy spectra at each time.

2, o-Ps (3γ) is normalized at continuous Compton-free region (480—500 keV)

3, pick-off spectrum

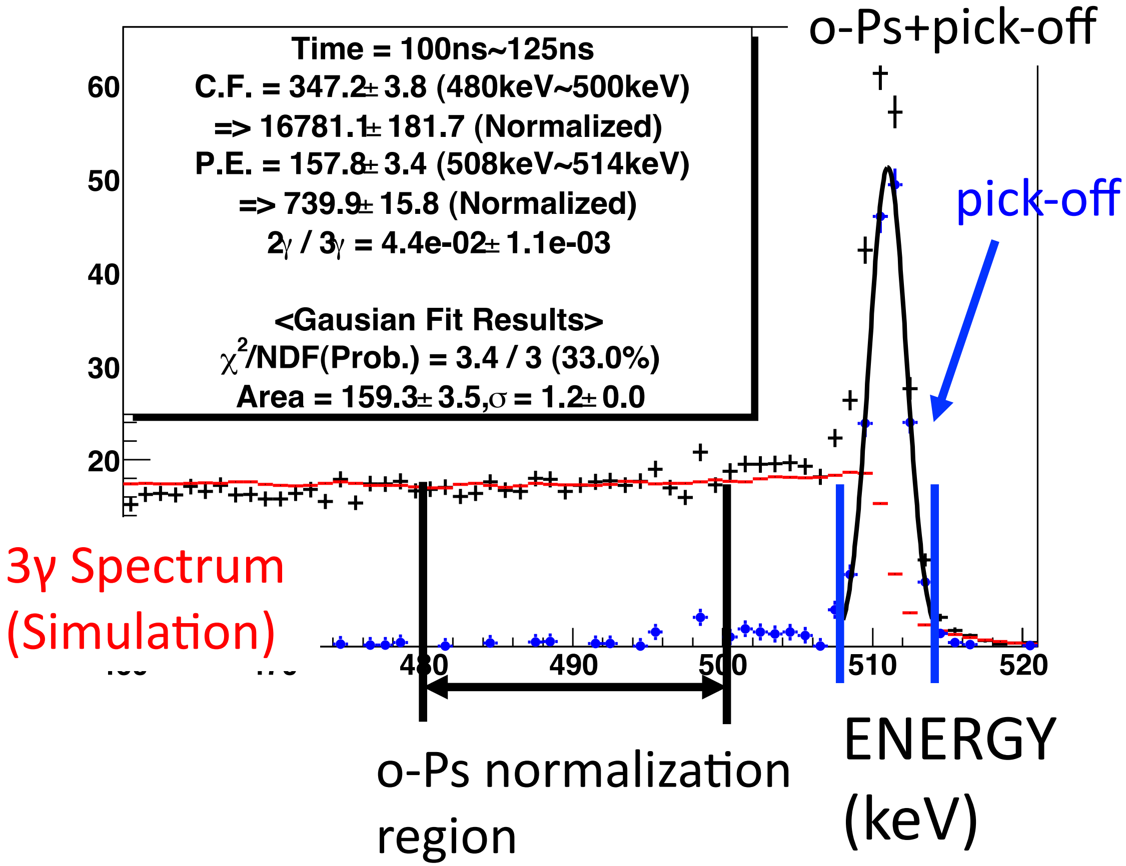
= data

– o-Ps spectrum

(count pickoff events in 508—514 keV)

4, Correction of o-Ps, Pick-off by MC simulation

$$v(t) \propto \frac{\text{pick-off } (2\gamma \text{ decay})}{\text{o-Ps } (3\gamma \text{ decay})}$$



ACAR

Angular Correlation of Annihilation Radiation

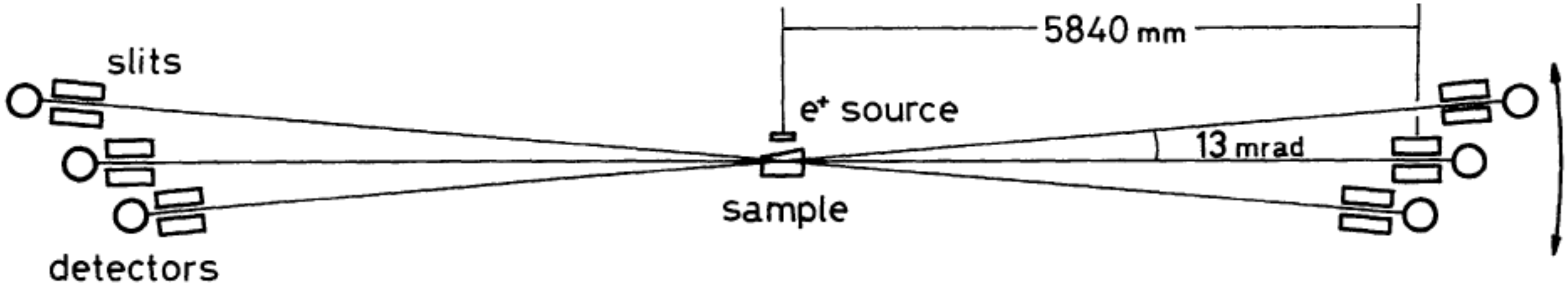


Fig. 1. One dimensional angular correlation apparatus having three pairs of long (800 mm) NaI(Tl) scintillation detectors. Adjacent pairs are separated by 13 milliradians.

Phys. Rev. A 52, 258 (1995)
J. Phys. B 31, 329 (1998)
J. Phys. B 36, 4191 (2003)

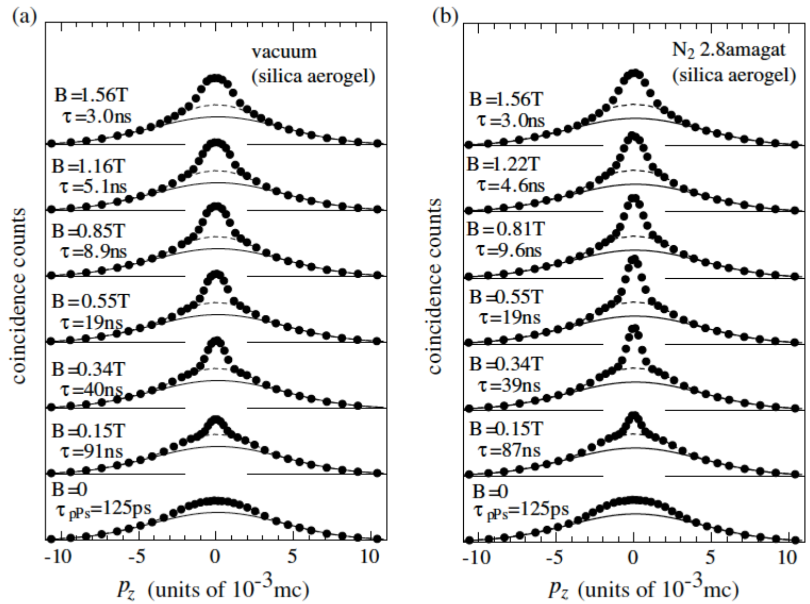


Figure 1. ACAR data for silica aerogel (a) in vacuum and (b) in 2.8 amagat of N_2. The full and broken curves indicate the broad component and the p-Ps component, respectively. The data are normalized to the broad component intensity. The magnetic flux density and the mean lifetime of o'-Ps, τ, are indicated in the figure. The mean lifetime of p-Ps, τ_{pPs}, is also indicated for the case of no magnetic field.

DBS

Doppler-Broadening Spectroscopy

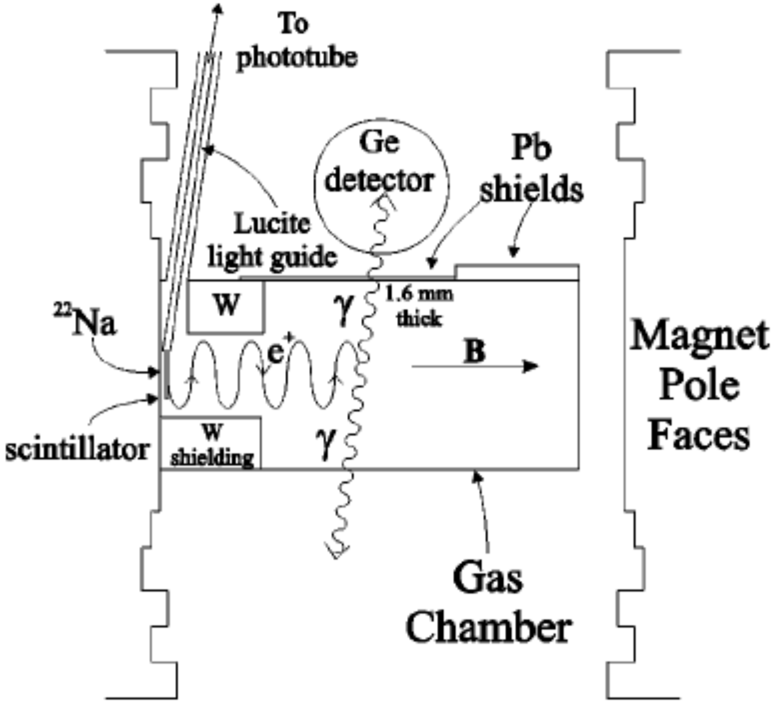


FIG. 2. Experimental apparatus. Positrons from ^{22}Na decay pass through a thin scintillator and enter a gas chamber. A magnetic field confines the trajectories near the axis. Positrons that stop in the gas can form Ps. Annihilation γ rays are detected in a Ge crystal.

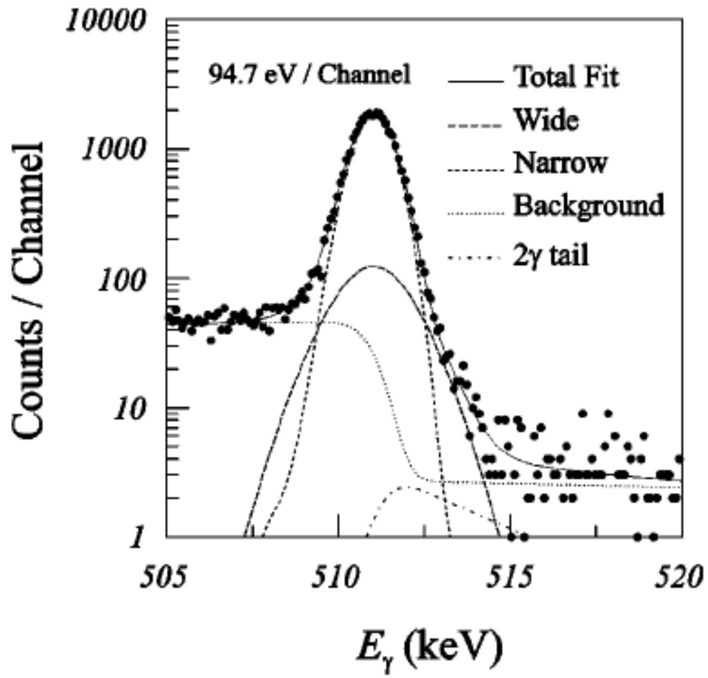


FIG. 3. Typical thermalization data. The Doppler-broadened 511-keV photopeak is resolved into two Gaussians, a step background, and a 2γ tail. The first three components are shown convoluted with the intrinsic detector resolution; the 2γ tail is also convoluted with the narrow Gaussian.

Phys. Rev. Lett. 80, 3727 (1998)
Phys. Rev. A 67, 022504 (2003)

Ps thermalization function

$$\frac{\mathrm{d}E_{\mathrm{av}}(t)}{\mathrm{d}t} = -\sqrt{2m_{\mathrm{Ps}}E_{\mathrm{av}}(t)}\left(E_{\mathrm{av}}(t) - \frac{3}{2}k_BT\right)\left(\frac{8}{3}\sqrt{\frac{2}{3\pi}}\frac{2\sigma_m n}{M} + \alpha\left(\frac{E_{\mathrm{av}}(t)}{k_BT}\right)^{\beta}\right)$$

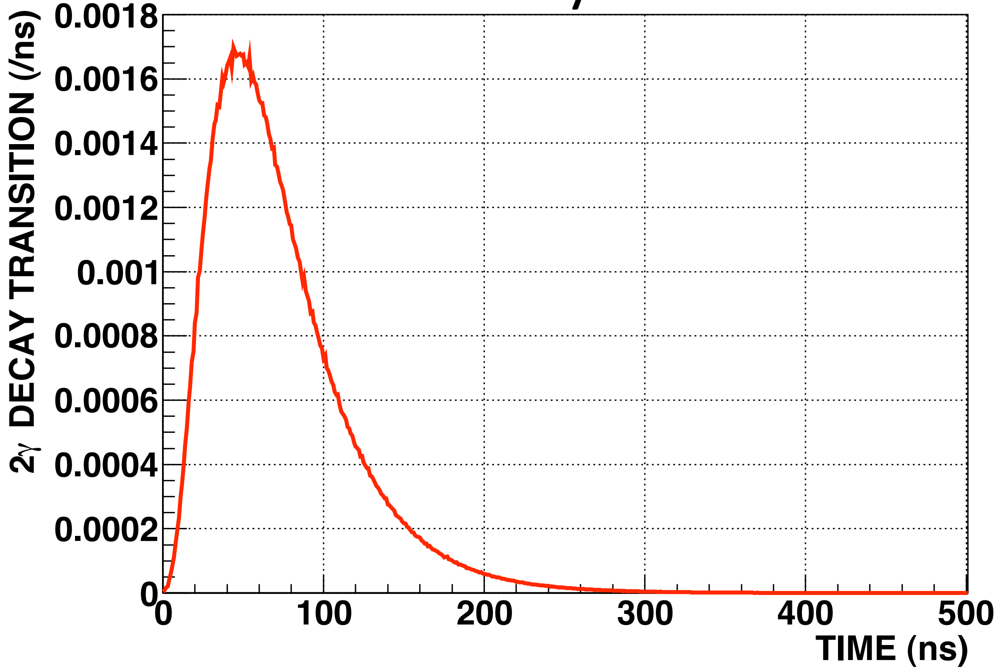
$$E_{\mathrm{av}}(t) = \left(\frac{1+Ae^{-bt}}{1-Ae^{-bt}}\right)^2\frac{3}{2}k_BT\,. \qquad b = \frac{8}{3}\sqrt{\frac{2}{3\pi}}\frac{2\sigma_m n}{M}\sqrt{3m_{\mathrm{Ps}}k_BT}$$

$$A = \frac{\sqrt{E_0} - \sqrt{\frac{3}{2}k_BT}}{\sqrt{E_0} + \sqrt{\frac{3}{2}k_BT}}$$

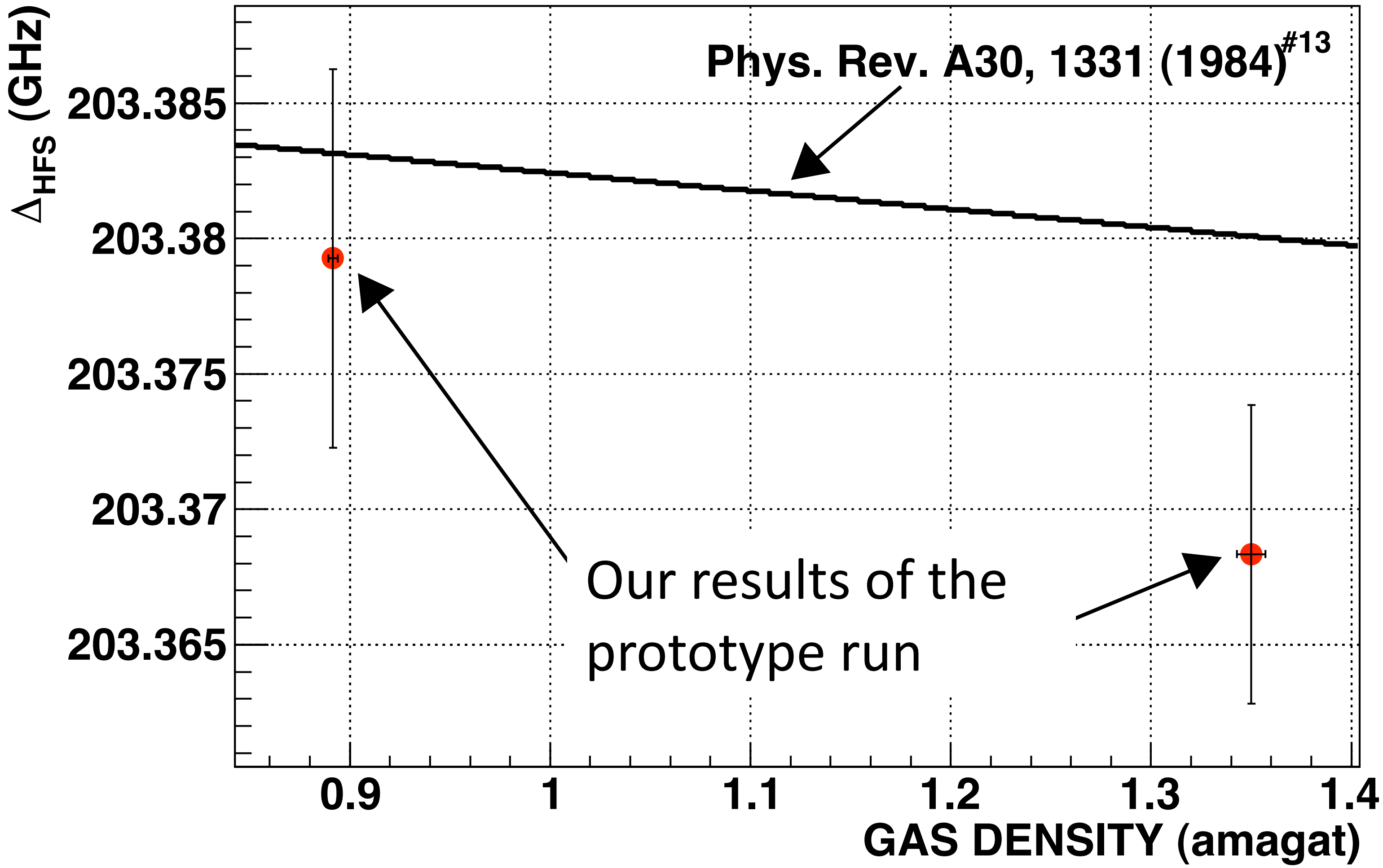
Gas	E_0 (eV)	σ_m (Å^2)
N_2	$2.07^{+0.04}_{-0.03}$	13.0 ± 0.5
iso-C_4H_{10}	$3.1^{+1.0}_{-0.7}$	146 ± 11

Weight Function:

Transition Probability



Gas Pressure Dependence



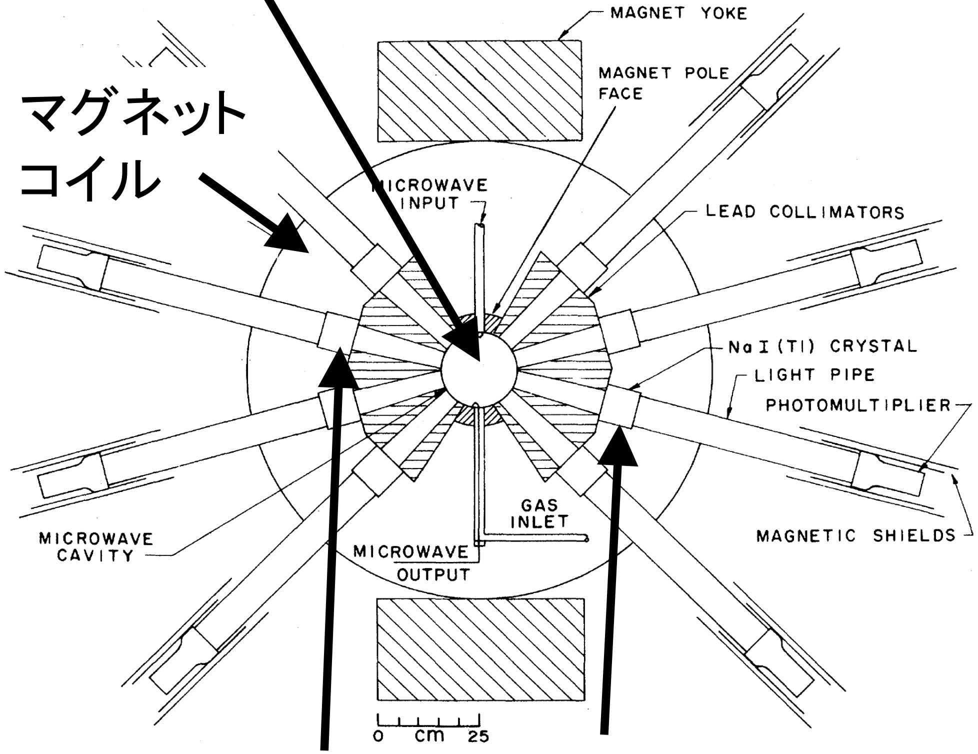
The pressure dependence is not clarified by our results of the prototype run, but it is consistent with the previous experiment.

→ Apply a correction of -33 ppm/atm (Ritter et al., 1984)

過去の実験と、考えられる系統誤差

RFキャビティーにガスを入れて
β^+線からポジトロニウムを生成

マグネット
コイル



NaI(Tl)シンチレータで
Back-to-backに測定

「磁石の神様」V. ヒューズらの
実験セットアップ(80年代)

系統誤差1. 磁場の非一様性

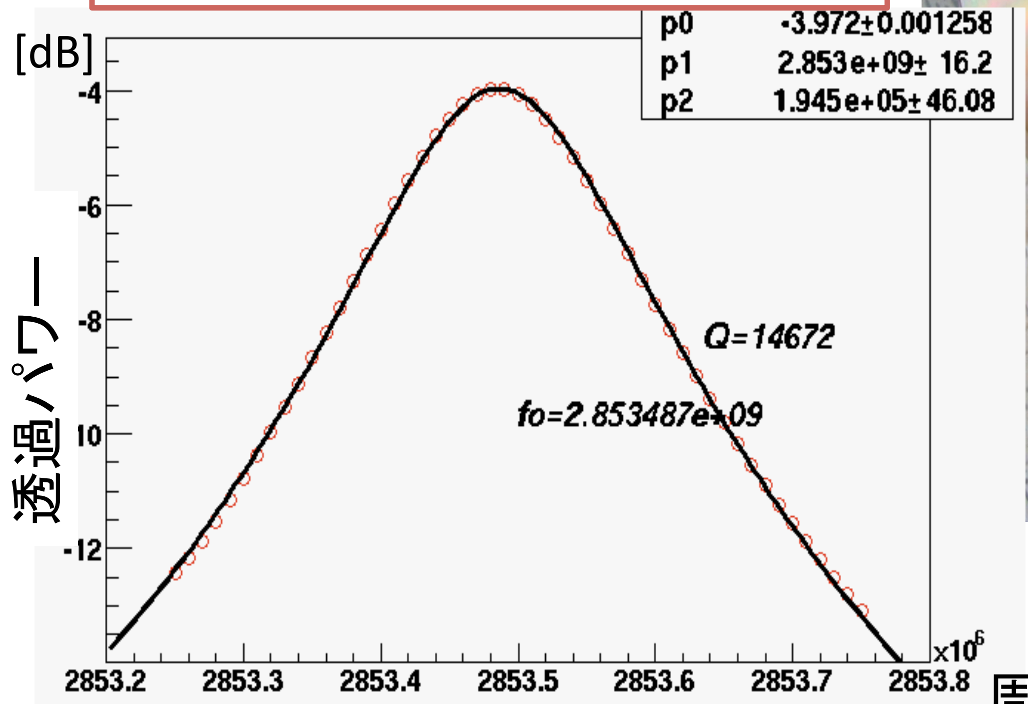
磁場の不定性がそのまま
測定結果の主な系統誤差に。
一方、ポジトロニウムの
生成領域は数cmに及ぶ。
→ 大きなサイズでppm精度での
磁場制御は非常に困難。

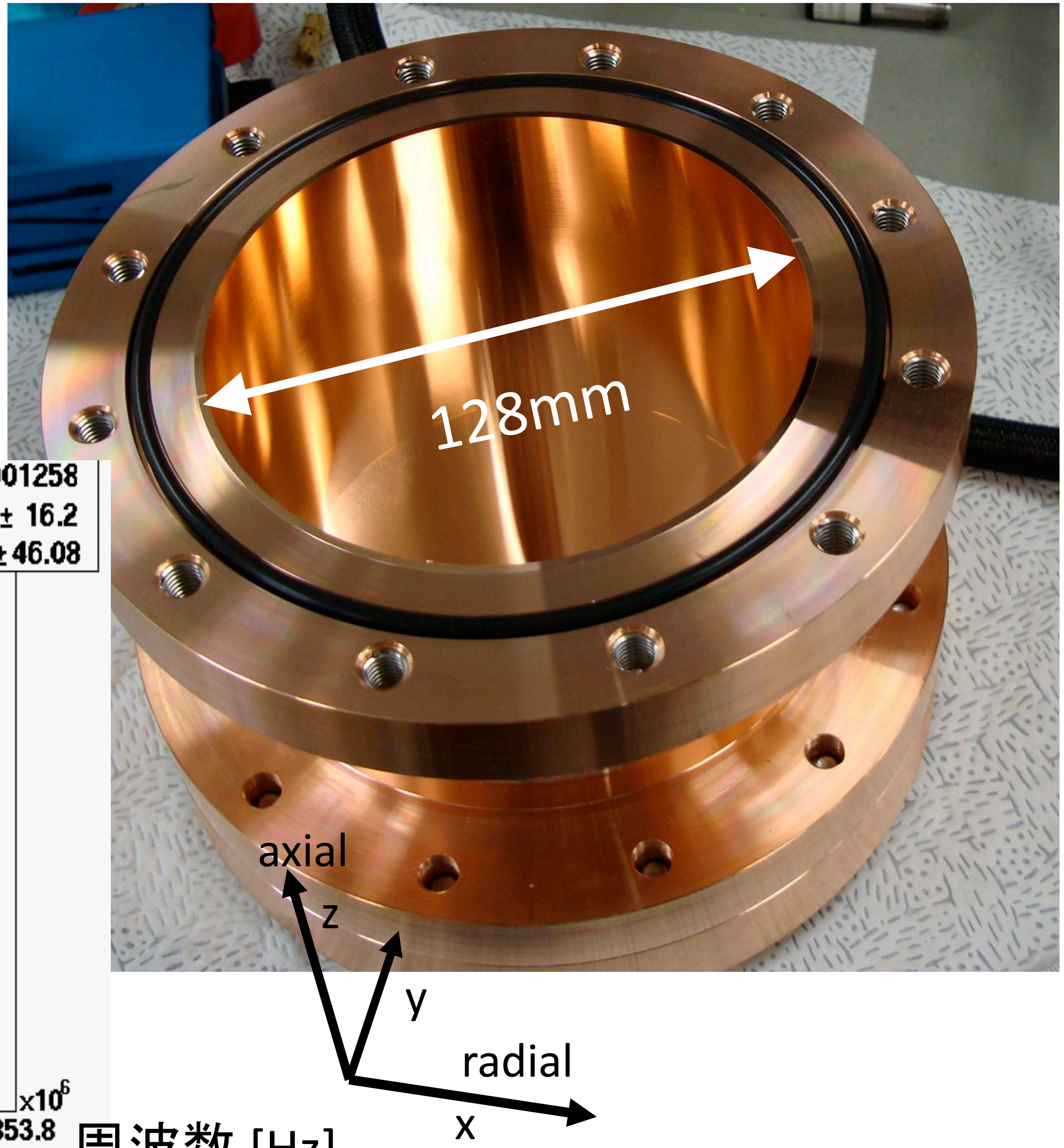
系統誤差2. 物質の効果

ポジトロニウム生成には、物質
(ここではガス)が必要不可欠だが、
物質は、HFSの値をずらしてしまう。
過去の実験では、物質の効果
の評価が、十分でなかった可能
性がある。

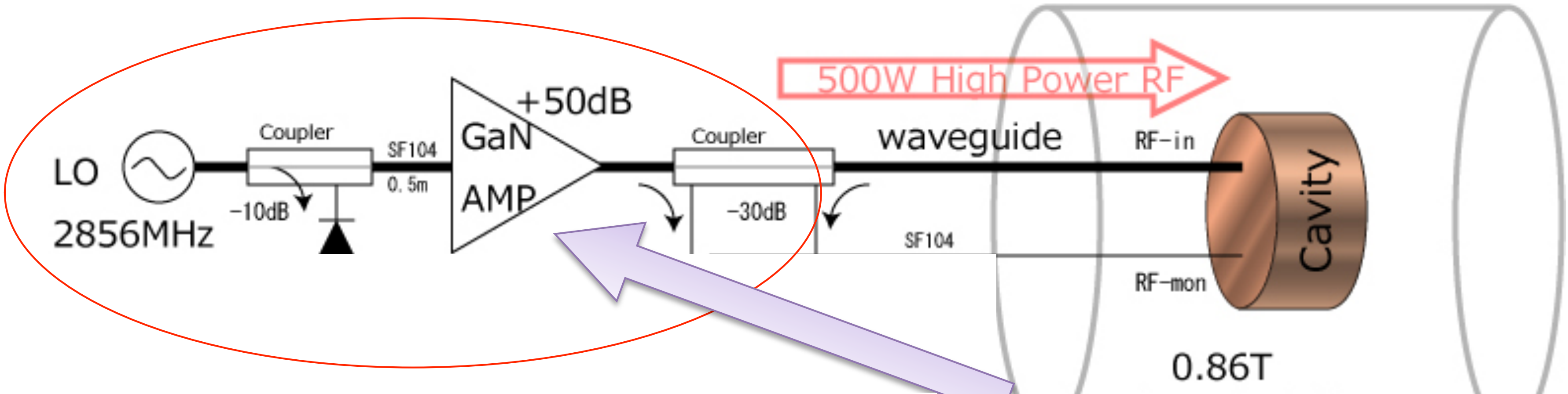
RF キャビティー

1. 共振周波数：2856MHz
2. 共振モード：TM_{110}
3. RF耐圧：500W [CW]
4. 側面厚(Cu)：2.0 mm
5. Q=14700

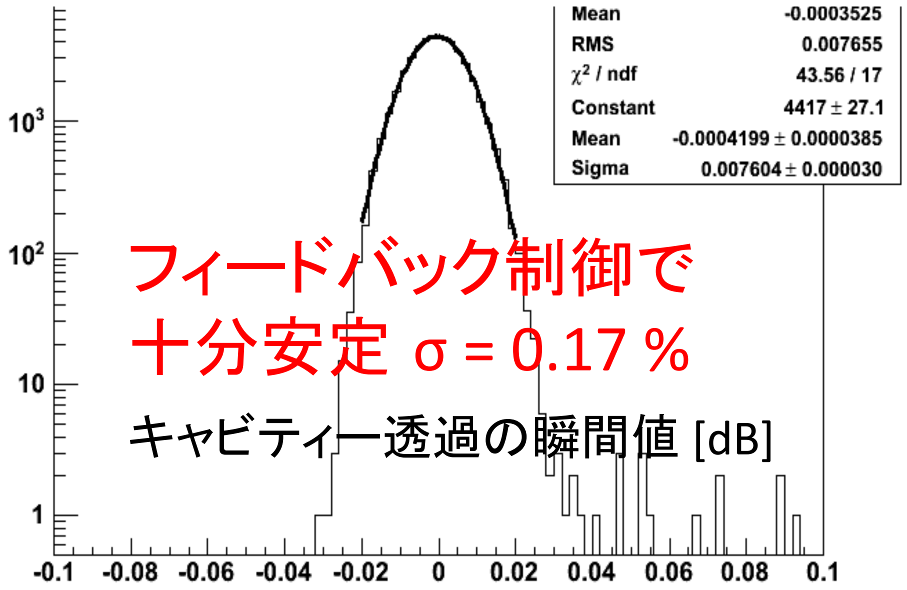


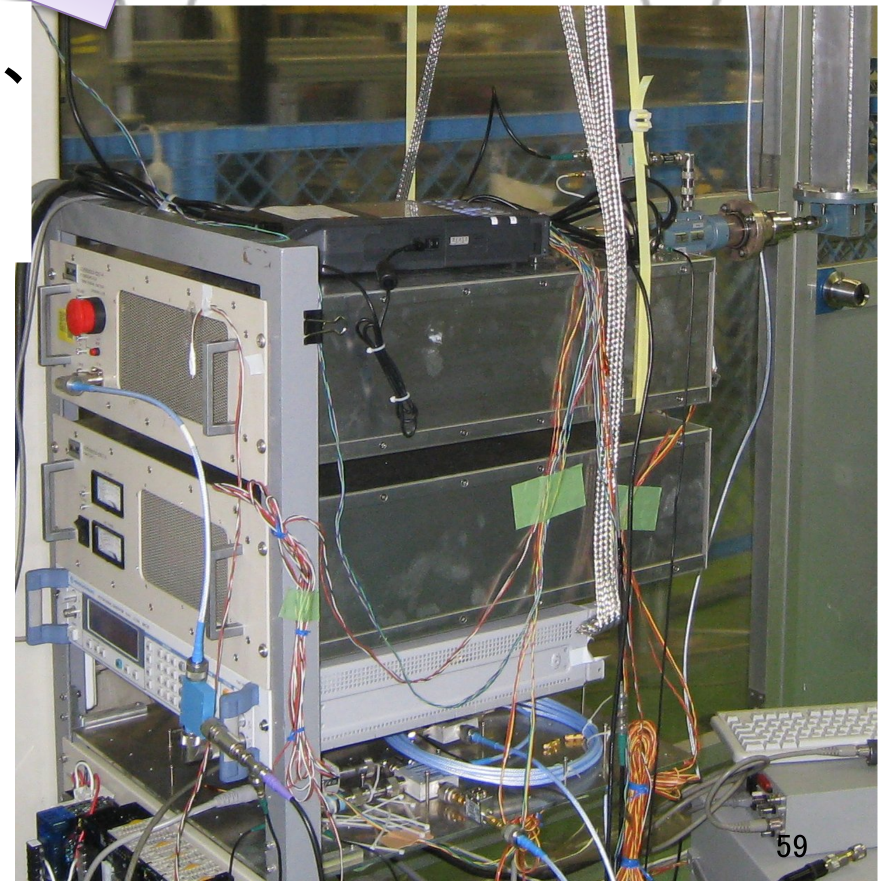


RF AMP

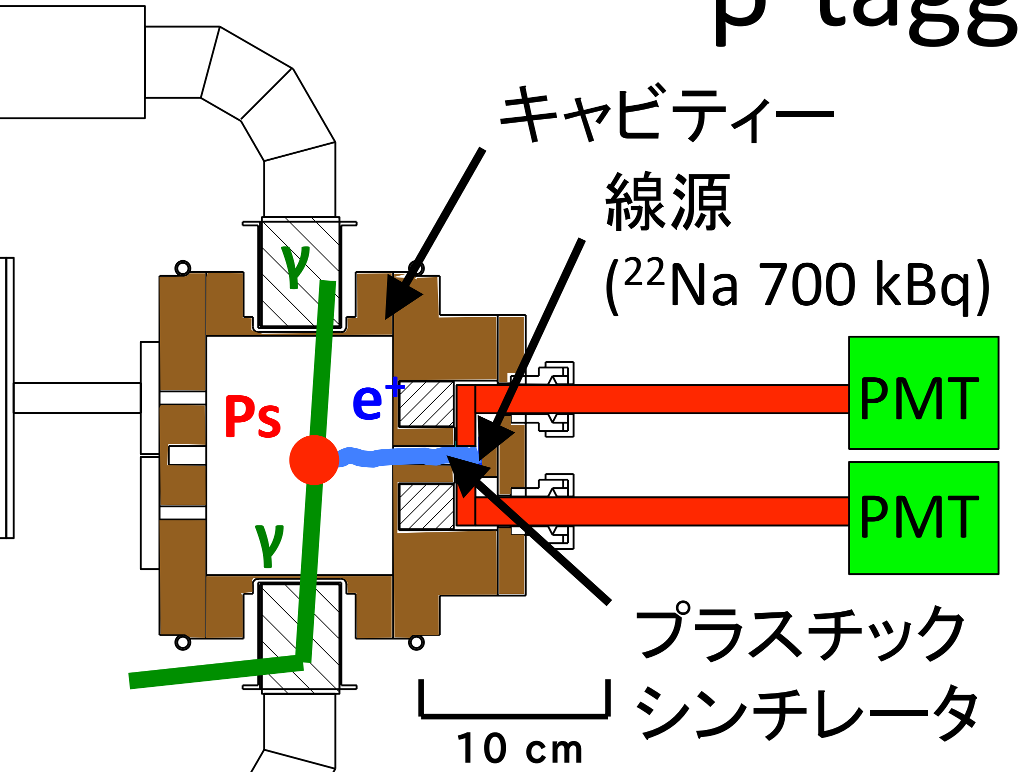


Signal Generatorで2856MHzのRFを出力、
GaN　AMPで +50dBの増幅をする。
キャビティー内には、409 W 入る。

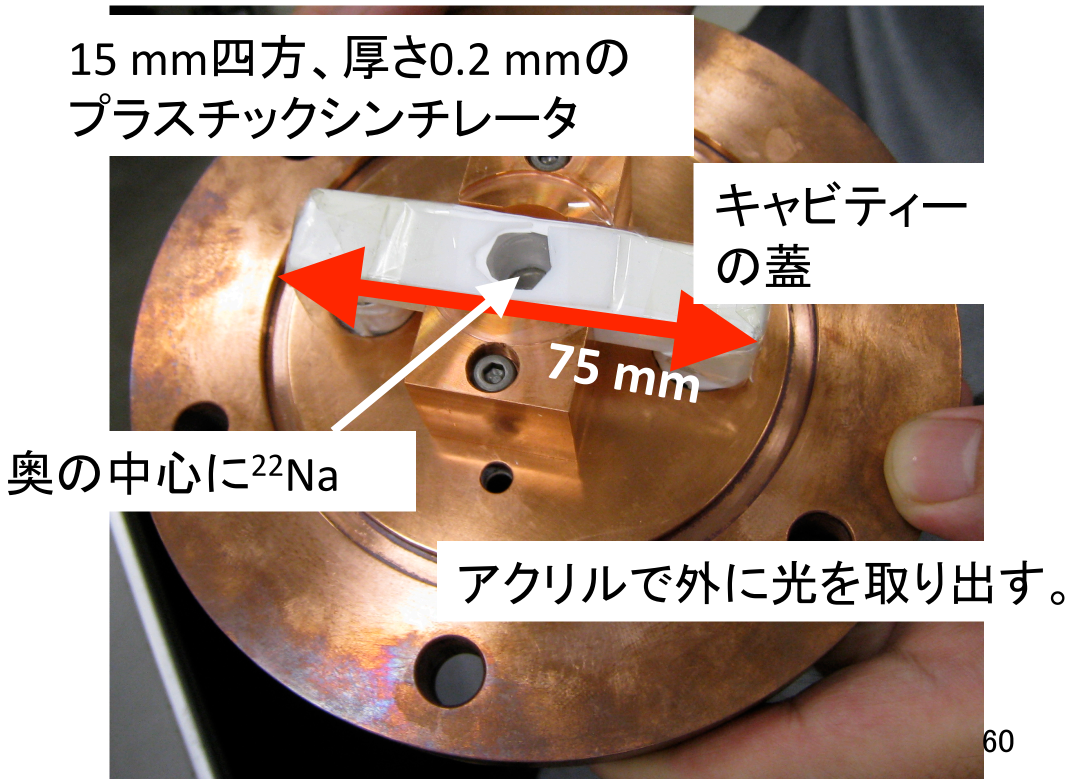




β-tagging system

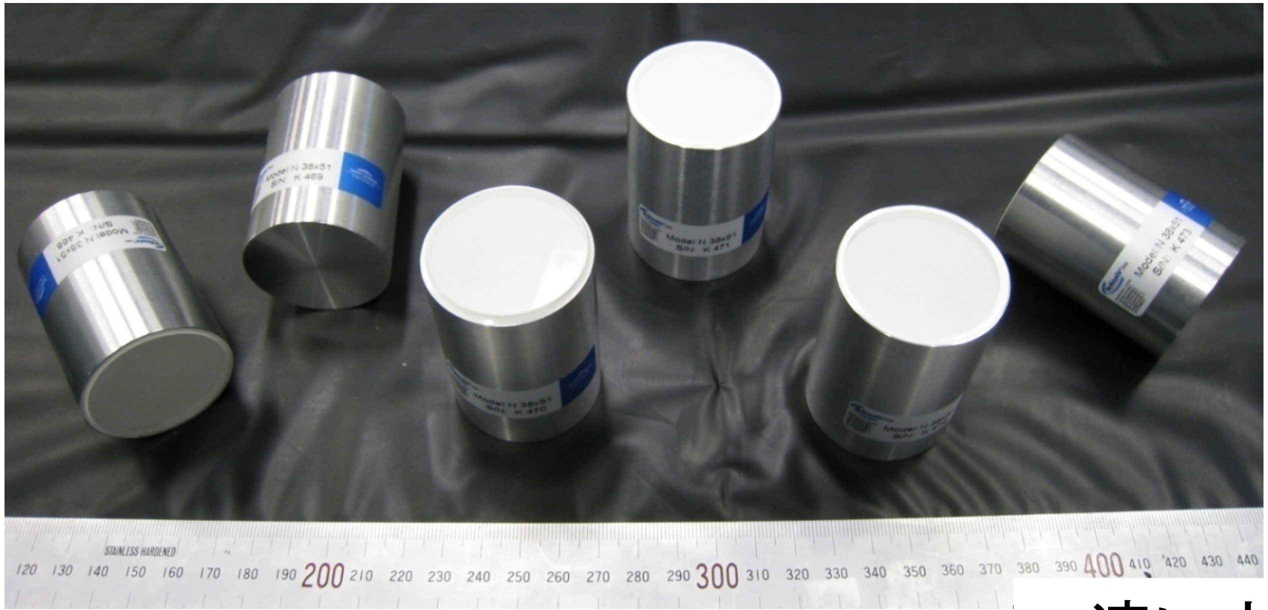


・プラスチックシンチレータを使って、線源から放出されたe^+をタグ。
・ シグナルは、ファインメッシュPMTで両側読み出し。
・ この時刻をポジトロニウム生成時刻(t=0)とする。



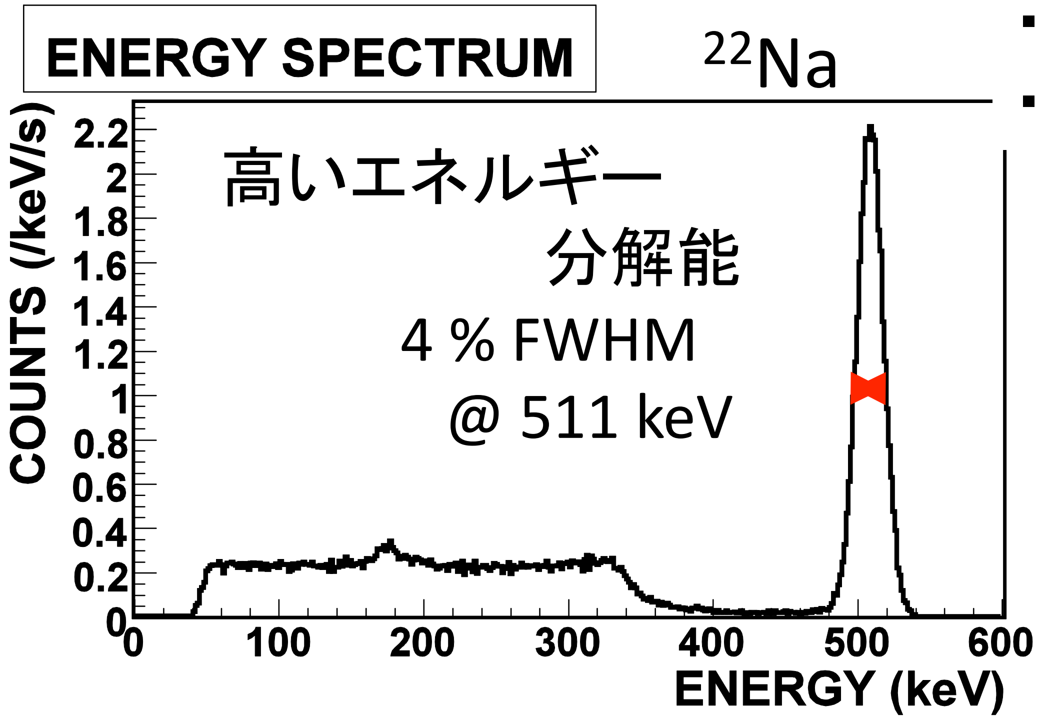
・2つのPMTのシグナルをコインシデンスする。
・ 十分な光量(~10p.e.)が得られることを確認。

ガンマ線検出器 (1) ～$LaBr_3$～



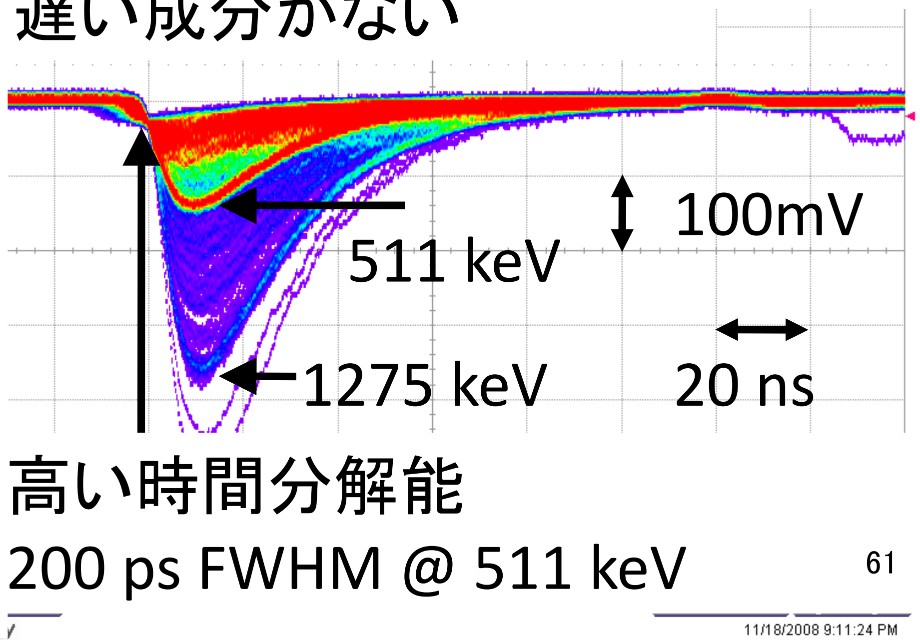
$LaBr_3$(Ce)シンチレータ
（直径1.5インチ、長さ2インチ）
を 6 個 使用

UVTライトガイドで光を導き、
ファインメッシュPMTで、
磁場中での読み出しを行う。



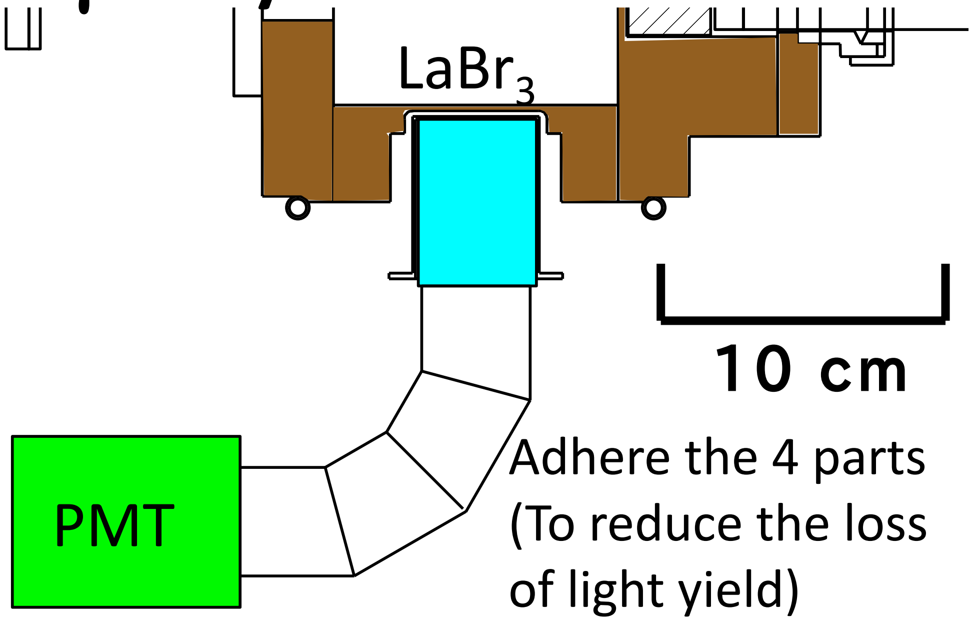
- 速い立ち上がり
- 遅い成分がない

^{22}Na



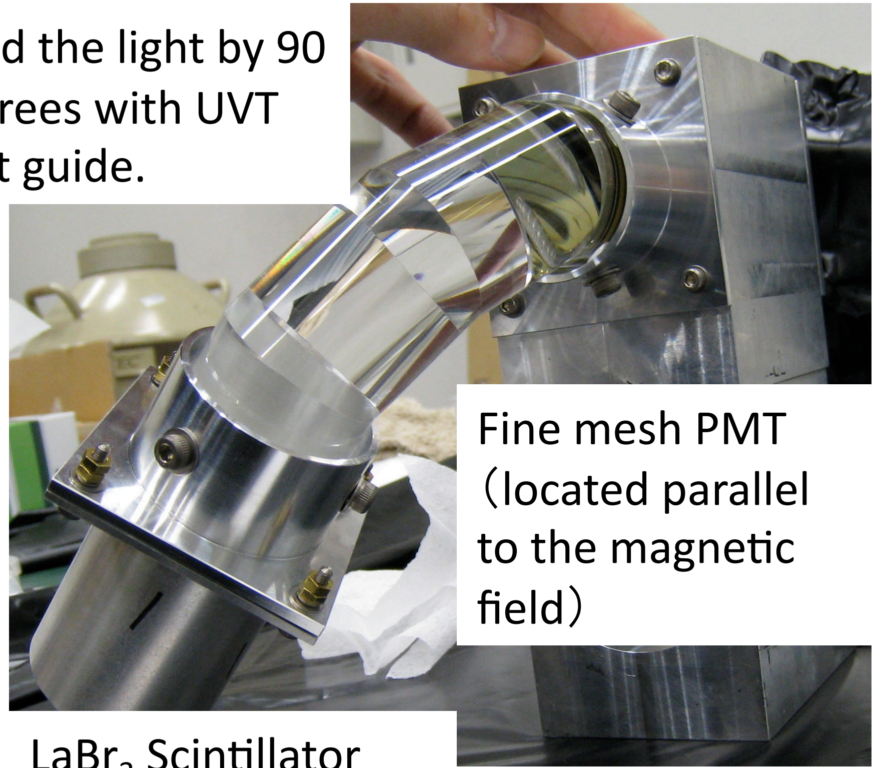
高い時間分解能
200 ps FWHM @ 511 keV

γ-ray Detectors ～UVT Light Guides～



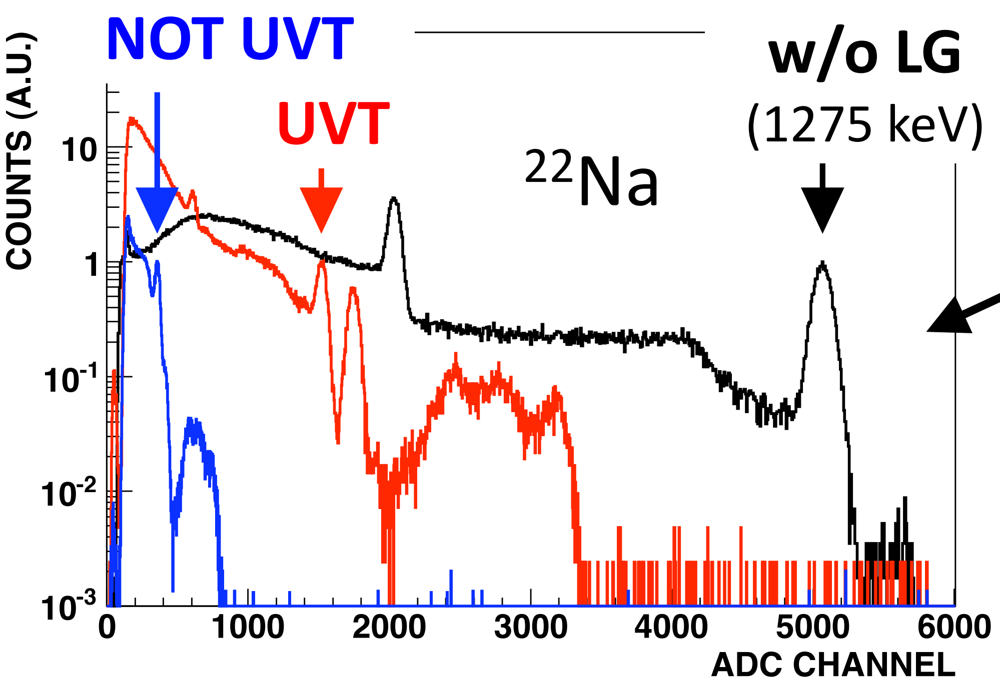
Adhere the 4 parts
(To reduce the loss
of light yield)

Bend the light by 90
degrees with UVT
light guide.



Fine mesh PMT
（located parallel
to the magnetic
field）

LaBr$_3$ Scintillator

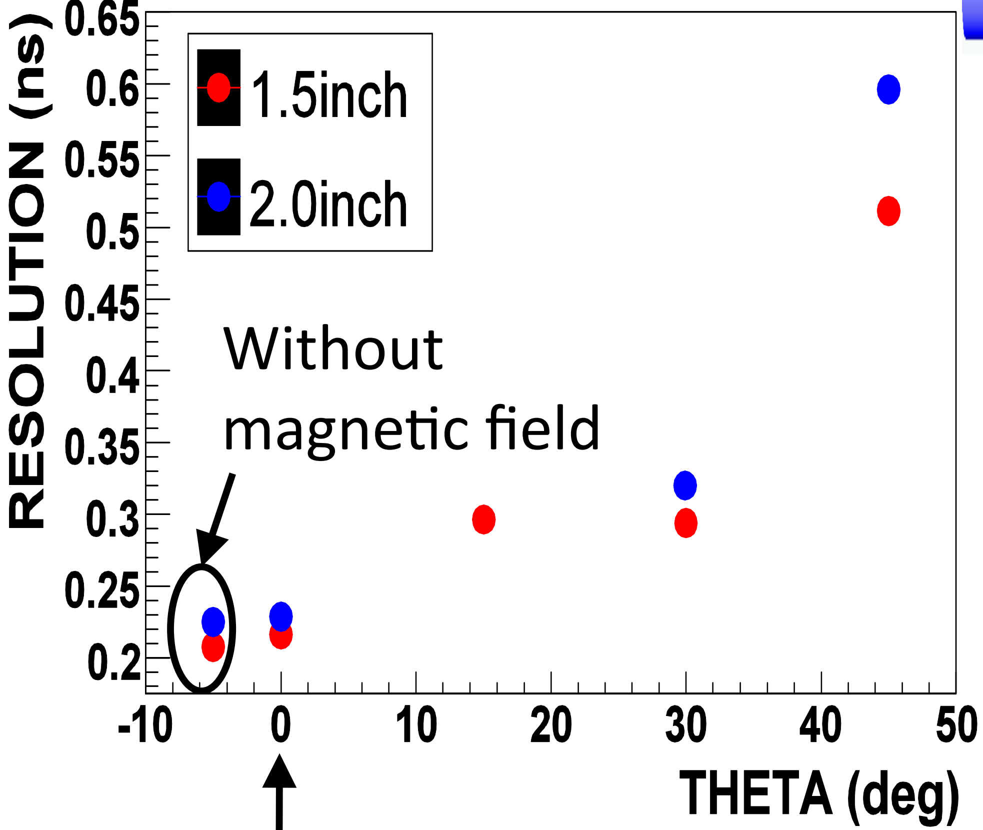


Change of light yield with light guides

Light yield with
UVT light guide is 30 % of that
without light guide.
(only 7 % with **NOT UVT** light guide)

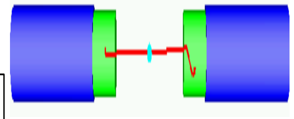
Angle (θ) dependence of Timing Resolution

FWHM @ 511 keV



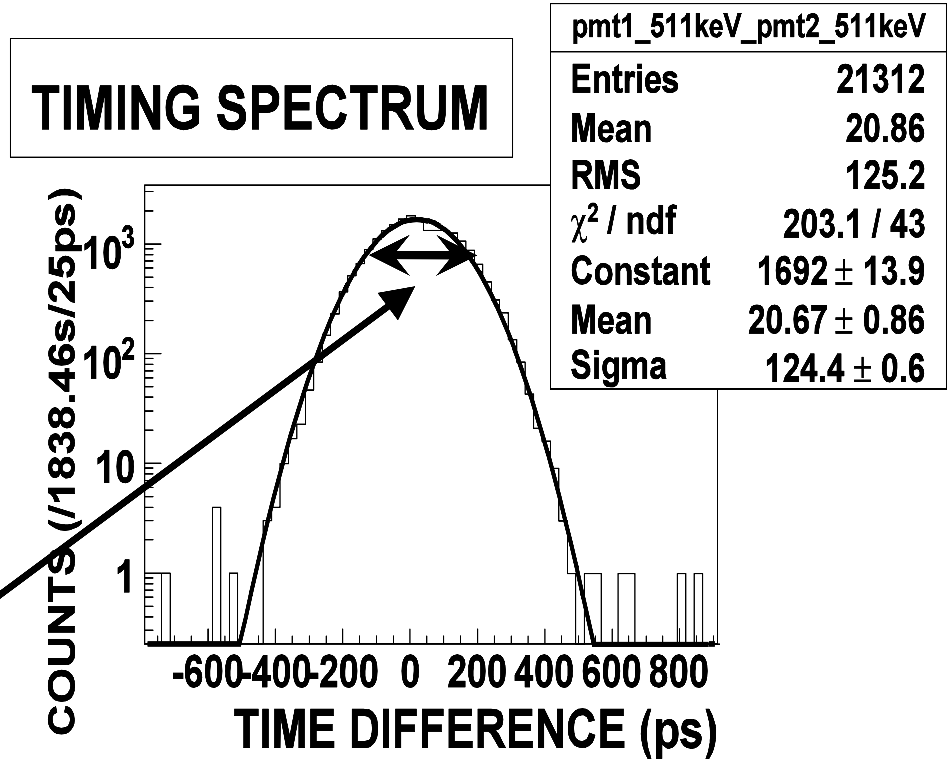
No change in 0°.

FWHM 293 ps @ 511 keV

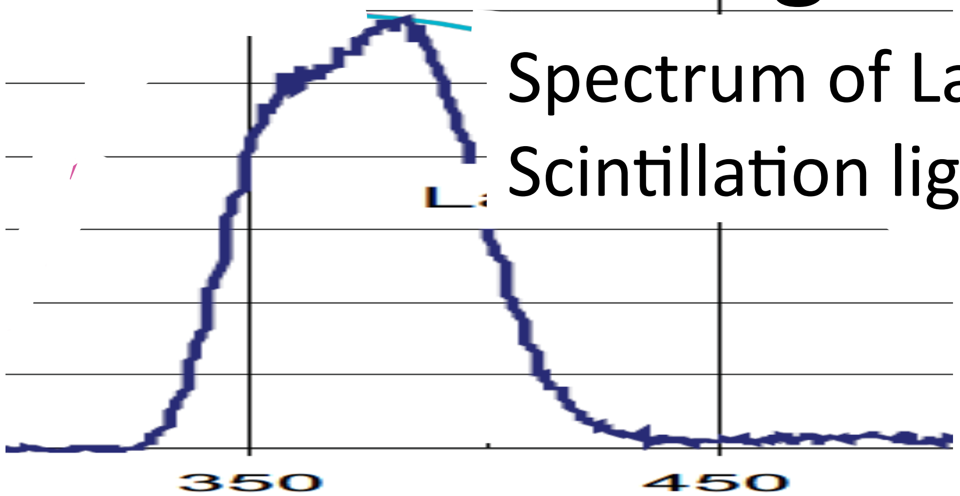


511 keV back-to-back

↓ Timing Difference without magnetic field（1.5 inch + 2.0 inch coincidence)

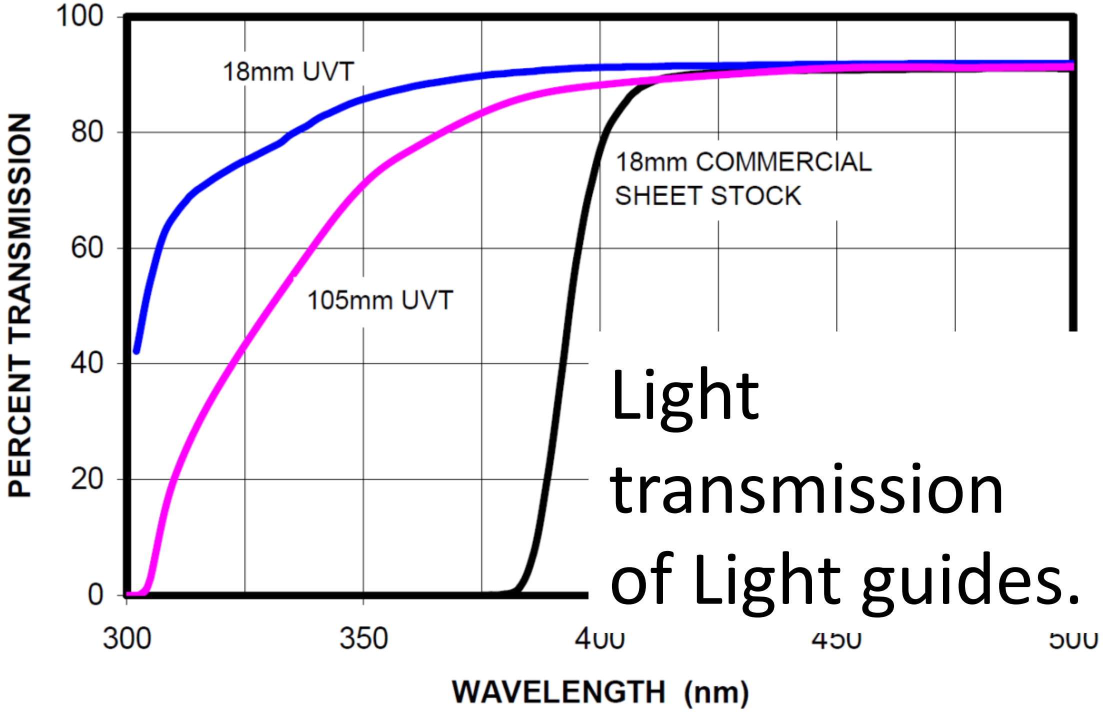


UVT Light guides



Spectrum of $LaBr_3$
Scintillation light

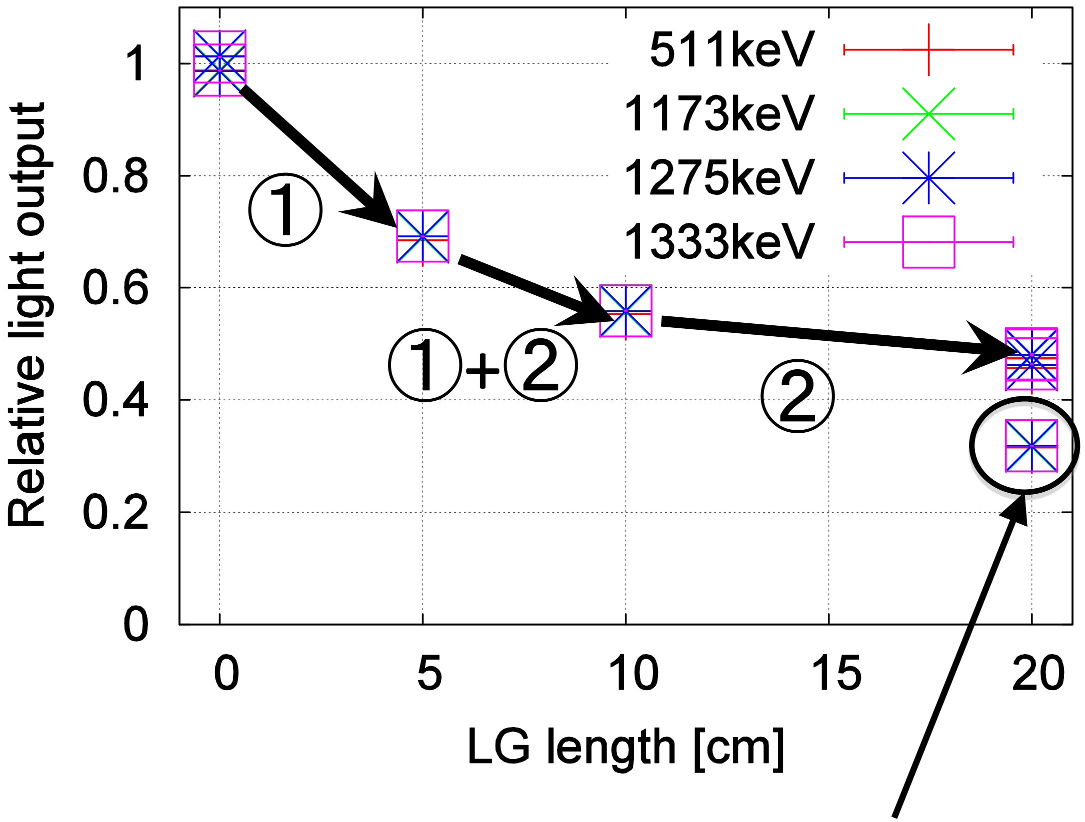
Wavelength of the $LaBr_3$ scintillation light is λ=380 nm.



Light transmission of Light guides.

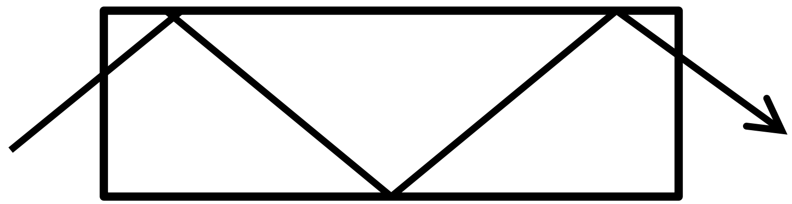
We use UVT (Ultra-Violet Transmitting) light guide.

Light guide length dependence of light attenuation



LG was not glued perfectly.

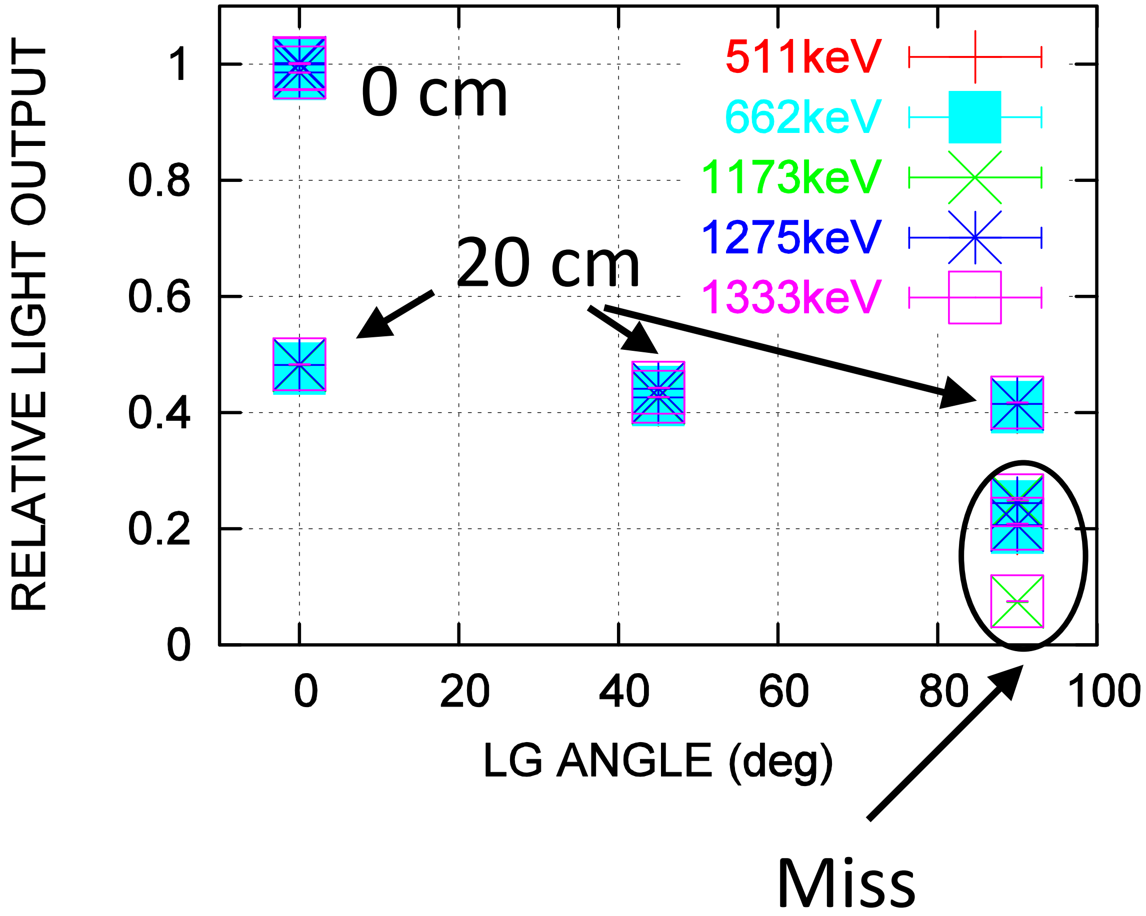
① Loss by total Reflection condition.



② Loss by absorption (small contribution).

Half at 20 cm, but it seems to be almost constant at this length.

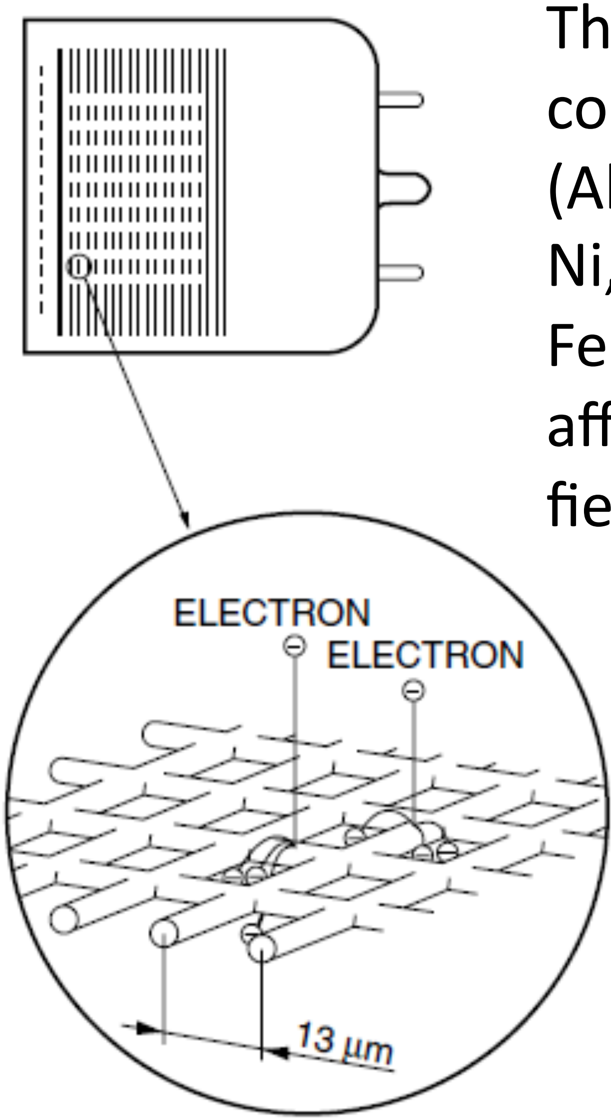
LG Binding Angle dependence



・ At 20 cm, there is no clear dependence on the binding angle.

・ Small effect by binding LG.

Fine Mesh PMT



FINE-MESH TYPE

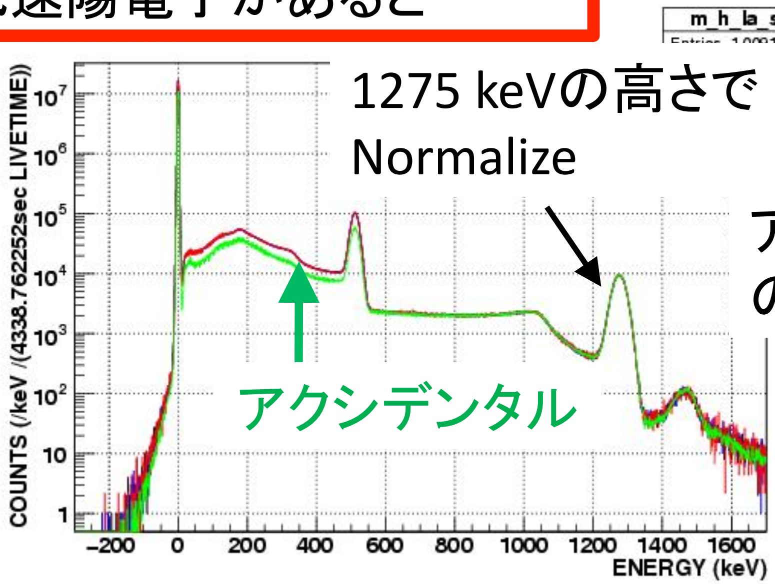
The Fine Mesh PMT contains Kovar (Alloy mainly of Fe, Ni, and Co. Ferromagnetic) and affects the magnetic field.

From the measurement at KEK,
A few cm from the center
→ 100 ppm
10 cm
→ 10 ppm

低速陽電子 (Slow Positron)

・ガス中で、陽電子は、ガス分子との衝突を繰り返し、エネルギーを失う。
・エネルギーを失ってほぼ止まった後、陽電子の多くは、遅くなったまま生き続け、Psを生成したり、対消滅したりせず、〜180 ns の寿命を持つ → 低速陽電子
・タイミングカットをかけて、アクシデンタルを引いても、低速陽電子が対消滅するときの2γが、大きなバックグラウンドとなる。
・2008年末のテスト測定では、これが大きな問題となった (30—400 ns タイミングウィンドウのなかで、アクシデンタルを引いた後のイベントの、60 %を、低速陽電子が占めていた)。
・イソブタンなどのガスは、低速陽電子の寿命を短くする、クエンチャーの能力がある。→ 今回の測定では、イソブタンを混ぜ、バックグラウンド除去に成功した。

低速陽電子があると……



アクシデンタルの引き算

アクシデンタルを引いても、
511 keV が残ってしまう。
(RF ONもOFFも同じに見える)

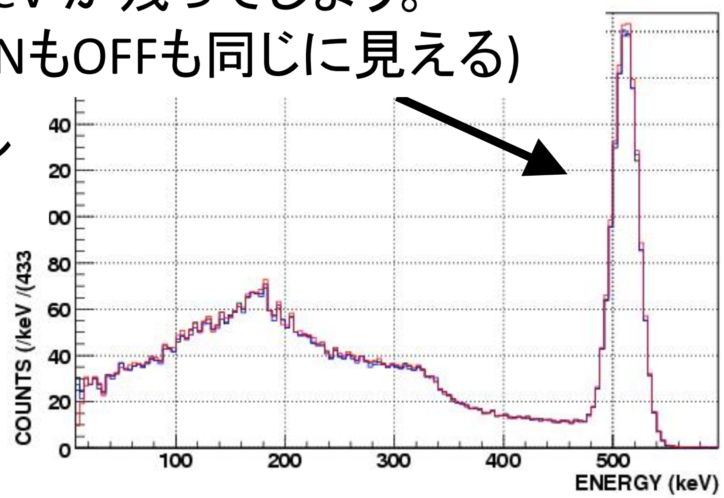
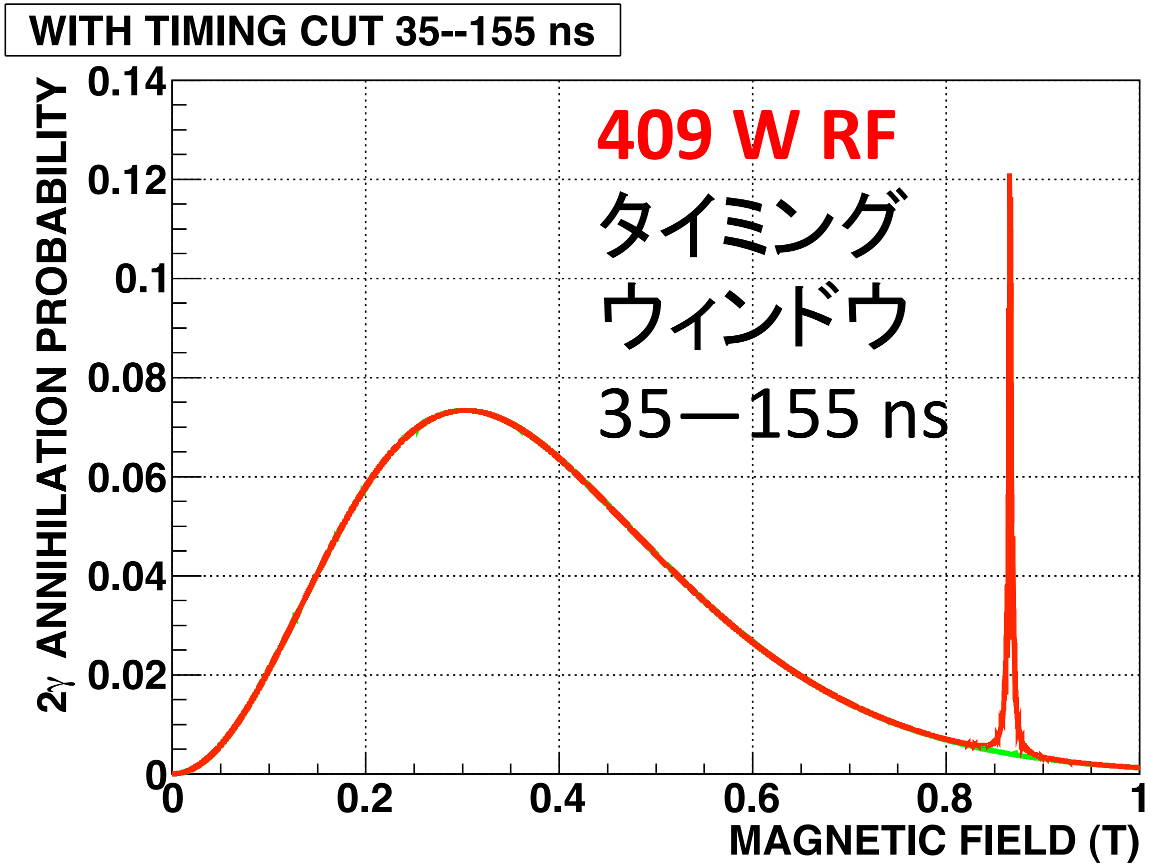


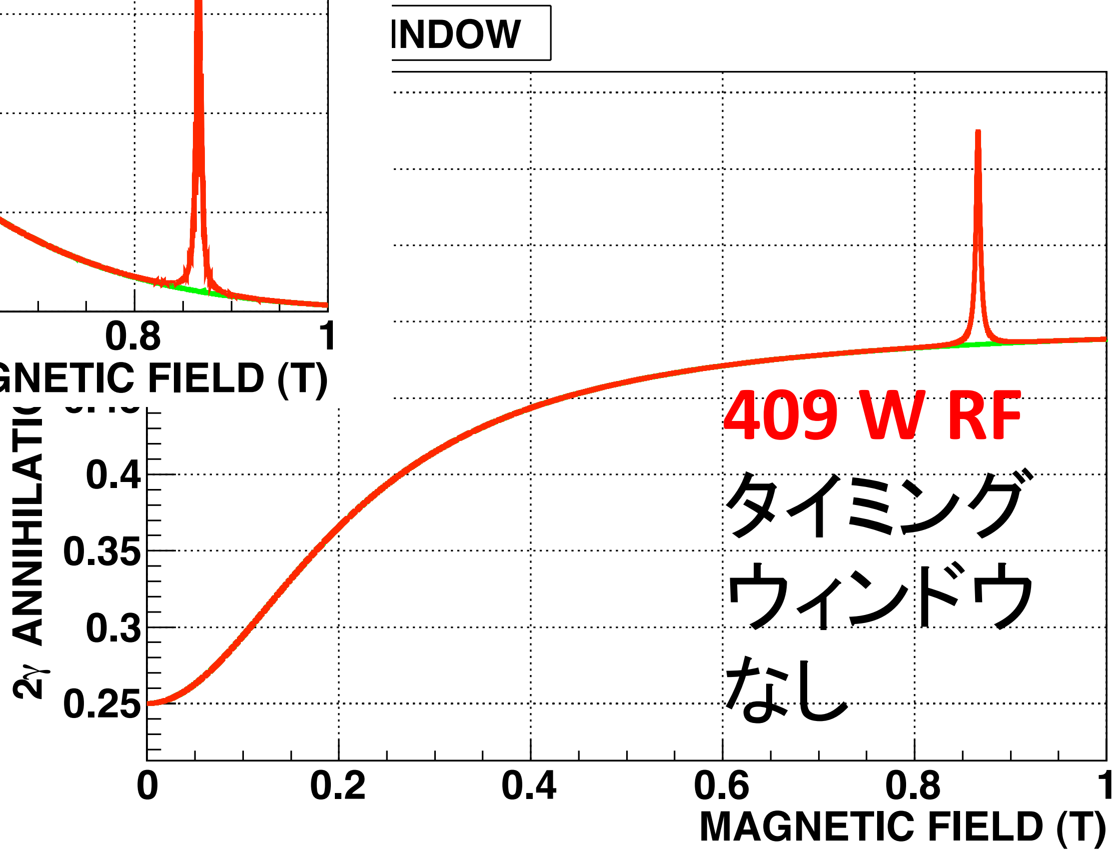
Table of Scintillator Properties

Scintillator	Density	Refractive index	Photons per MeV	Emission Maximum	Decay Constant	Radiation Length
	g / cm^3			nm	ns	cm
NaI (Tl)	3.67	1.85	38000	415	230	2.59
CsI (Tl)	4.51	1.79	59000	565	1000	1.86
LYSO	7.25	1.81	32000	420	40	1.15
YAP (Ce)	5.55	1.93	19700	347	28	2.7
$LaBr_3$(Ce)	5.08	1.9	63000	380	16	1.88

2γ崩壊確率



タイミングウィンドウ による
2γ崩壊確率の違い。
タイミングウィンドウ によって
BGを減らすことができる。
(図はQ_L=14700の理論値)



タイミングウィンドウ の選び方