Precise measurements of the positronium decay rate and energy level

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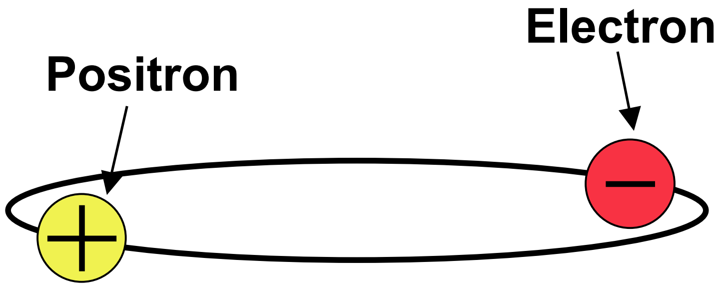
Positronium: Ps

Ps is the bound state of e^+ and e^-, and the lightest atom. Ps is a clean and excellent target to study “Bound state” QED.



Furthermore Ps is particle- antiparticle system, interesting for high energy physicist.

$\vec{S}$ =1(triplet) orthopositronium (o-Ps)

o-Ps → 3γ、(5γ, 7γ..)

=0 (Singlet) parapositronium (p-Ps)

p-Ps → 2γ、(4γ, 6γ…)

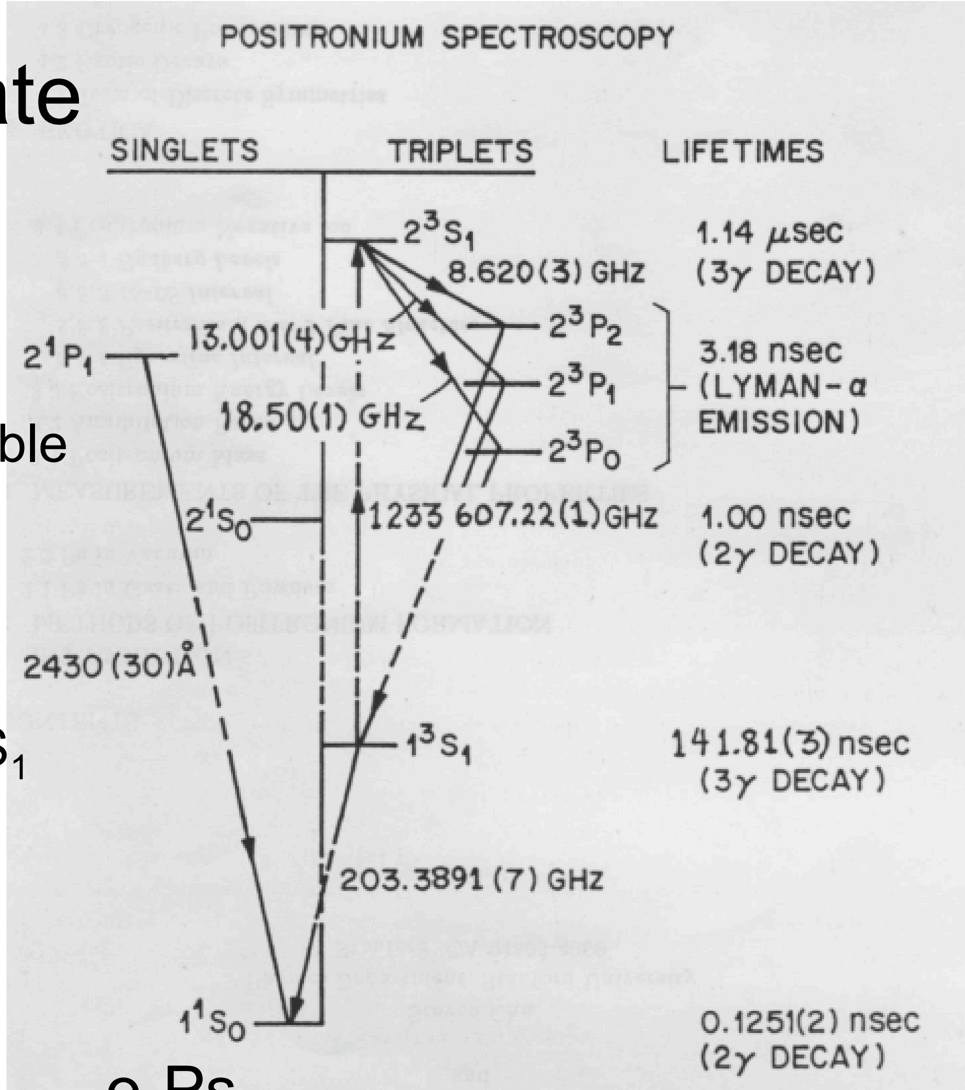
higher multiplicity decay is suppressed by 10^{-6}.
so only 3 and 2 γ decay is enough for study.

1/λ(o-Ps)=142.05 nsec and this is slow, we have a good chance to measure **the decay rate directly and precisely**.
It is good probe to study the higher order correction of “Bound state QED”.

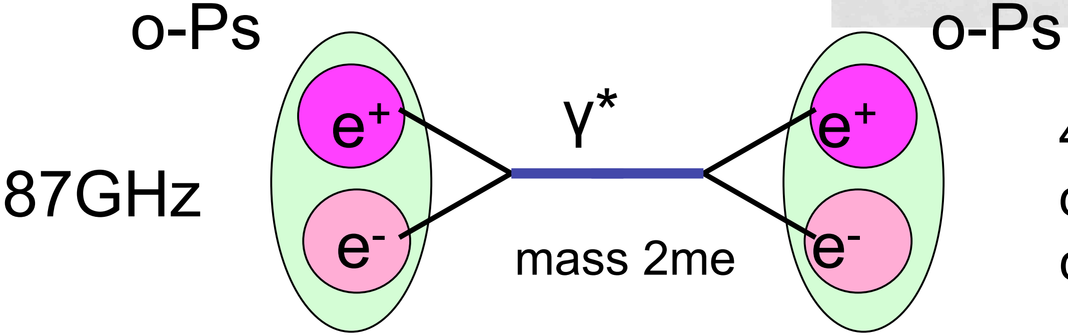
Energy level of Ps state

Ps has a rich structure of energy level,since magnetic moment of e± is large, then the spin-spin interaction has a sizable contribution,

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



Energy split between 1 $^1S_0$ and 1 $^3S_1$ is about 203GHz, which is sensitive higher order QED cal. and the new Physics.



40% comes from this quantum oscillation, and a new physics contribute on the propagator.

Accurate calculations of the Bound state QED are difficult and has been developed recently.

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Table 15
Theory of the annihilation decay rate of ortho- and parapositronium (the 1S state)

Contribution	Decay rate of orthopositronium (μs^{-1})	Decay rate of parapositronium (μs^{-1})
$\Gamma^{(0)}$	7.211 17	8 032.50
QED1	−0.172 30	−47.25
QED2	0.001 11(1), [186] ←	4.43(1), [187] ←
QED3	−0.000 01(2), [61,188]	−0.08(4), [61,188]
Total	7.039 96(2)	7989.62(4)

The leading contributions are defined above in Table 12. The decay rate of ortho/parapositronium into five/four photons is included into corresponding QED2 terms.

$o(\alpha^2)$ 100ppm level correction are calculated in 2000

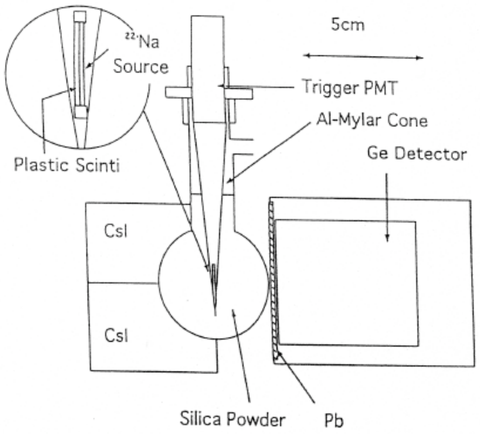
Table 13
Theory of the 1S hyperfine interval in positronium

Term		Fractional contribution	ΔE (MHz)	References
E_F	$\alpha^4 mc^2$	1.000 000 0	204 386.6	
QED1	$\alpha^5 mc^2$	−0.004 919 6	−1 005.5	
QED2	$\alpha^6 mc^2$	0.000 057 7	11.8	[184]
QED3	$\alpha^7 mc^2$	−0.000 006 1(22)	−1.2(6) ←	[61,149,150,185]
Total		0.995 132 1(22)	203 391.7(6)	

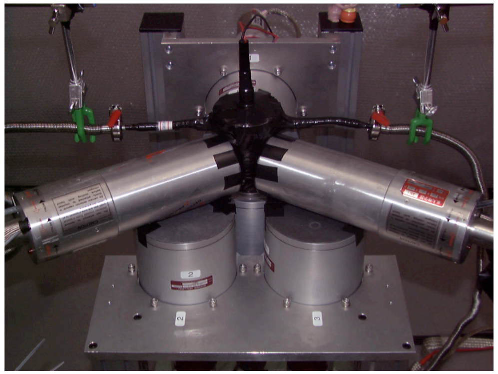
$o(\alpha^3)$, 6ppm level correction, are calculated in 2001

➡ Precision measurements with these accuracy are target of our study

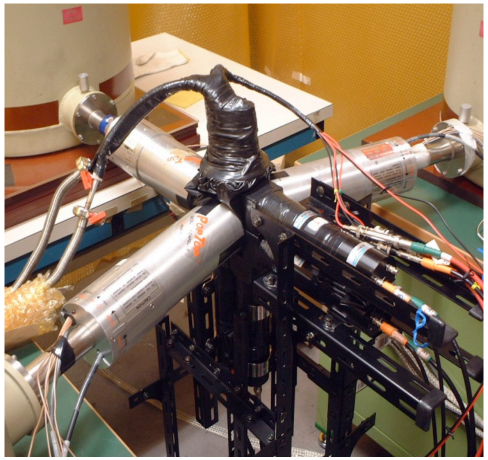
[1] o-Ps decay rate



1995

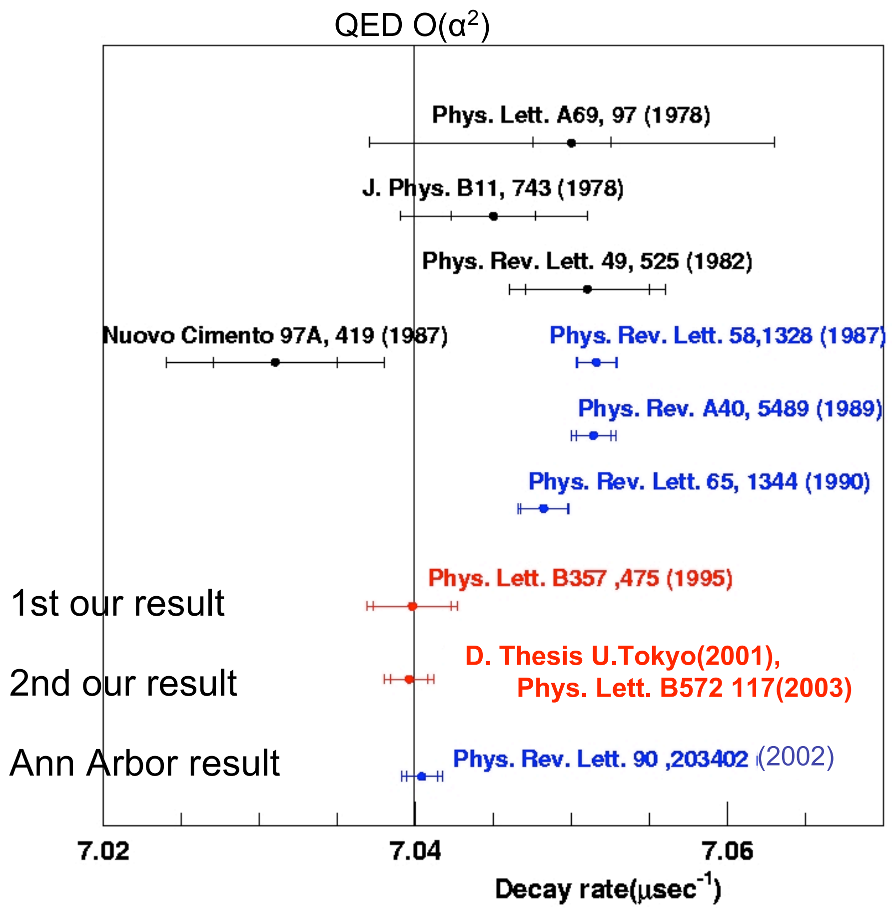


2001



2007

History of the measured decay rates of o-Ps



Before 1995, the measured decay rates were significantly higher than the QED calculation by about 1000ppm.

These results were consistent with each other and not statistical.

This discrepancy was called "o-Ps lifetime Puzzle".

In 1995 we proposed the new method to solve the common systematic problem of the previous all measurements (= non-thermalization problem).

We obtained the new result consistent with the QED calculations and differ from the old results.

After recognize this problem, the accuracy of the experiment becomes higher, and we have a chance to validate $O(\alpha^2)$ prediction.

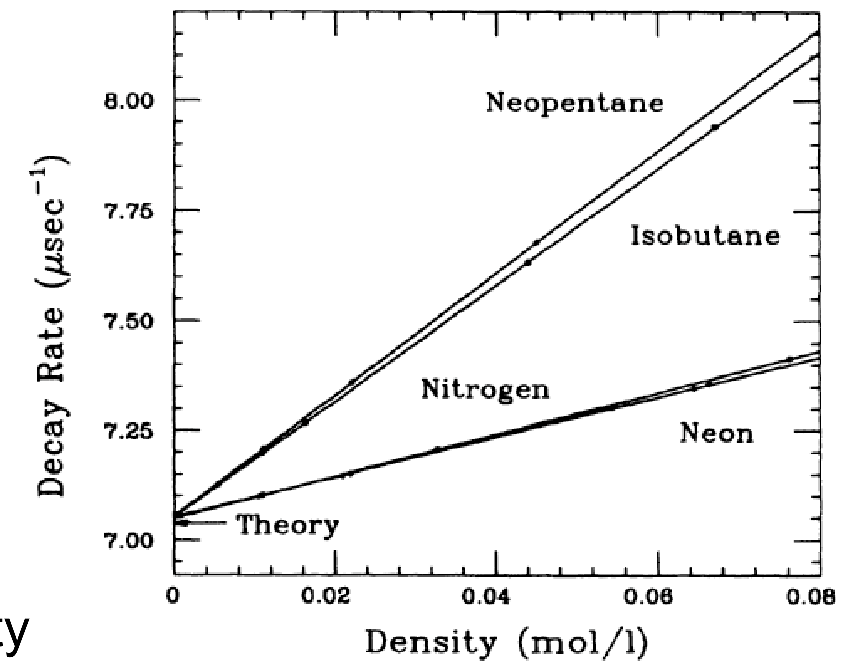
Pick-off annihilation (Material effect)

Ps is produced with β^+ source and materials(gas,SiO_2,cavity wall). The material is necessary to produce Ps (e^- provider), but it is also the source of the background. Rarely the collided o-Ps annihilates into 2 γ instantaneously (Pick-off annihilation) It is inevitable effect, and should be correct.

$$\lambda_{obs} = \lambda_{3\gamma} + \lambda_{pickoff}$$

If the mean velocity of o-Ps is constant
→ the collision rate is proportional to density of the material.
→ Material effect, $\lambda_{pickoff}$, is also proportional to density of the material.

So λ_{obs} is measured changing density, and extrapolate to “zero” density and obtain $\lambda_{3\gamma}$



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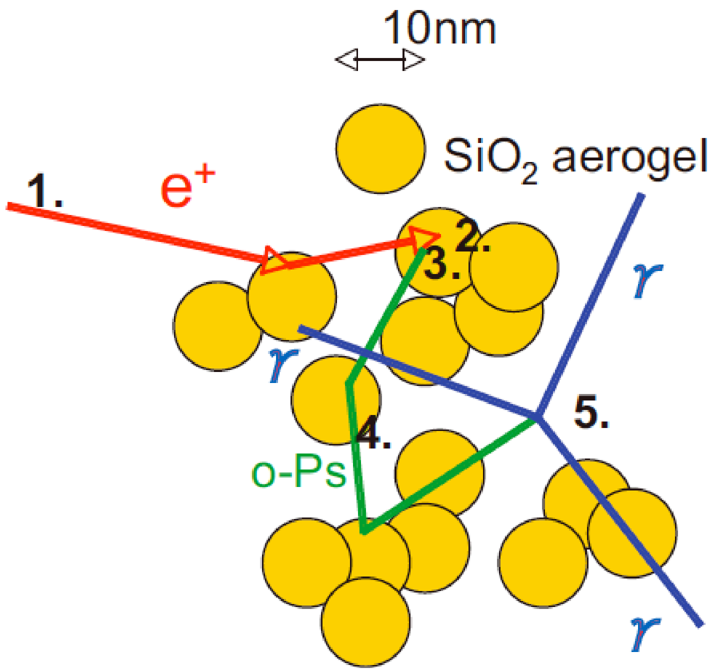
This is common method to all the experiments before 1995.

Non-thermalization problem

The produced positronium has kinetic energy (∽1eV), and collides elastically the material frequently. Ps looses the kinetic energy gradually, and the energy becomes 1/30 eV (Thermalization process):



If o-Ps is not well thermalized,
→ the mean velocity is higher and the collision rate is higher
→ $\lambda_{pickoff}$ becomes higher.

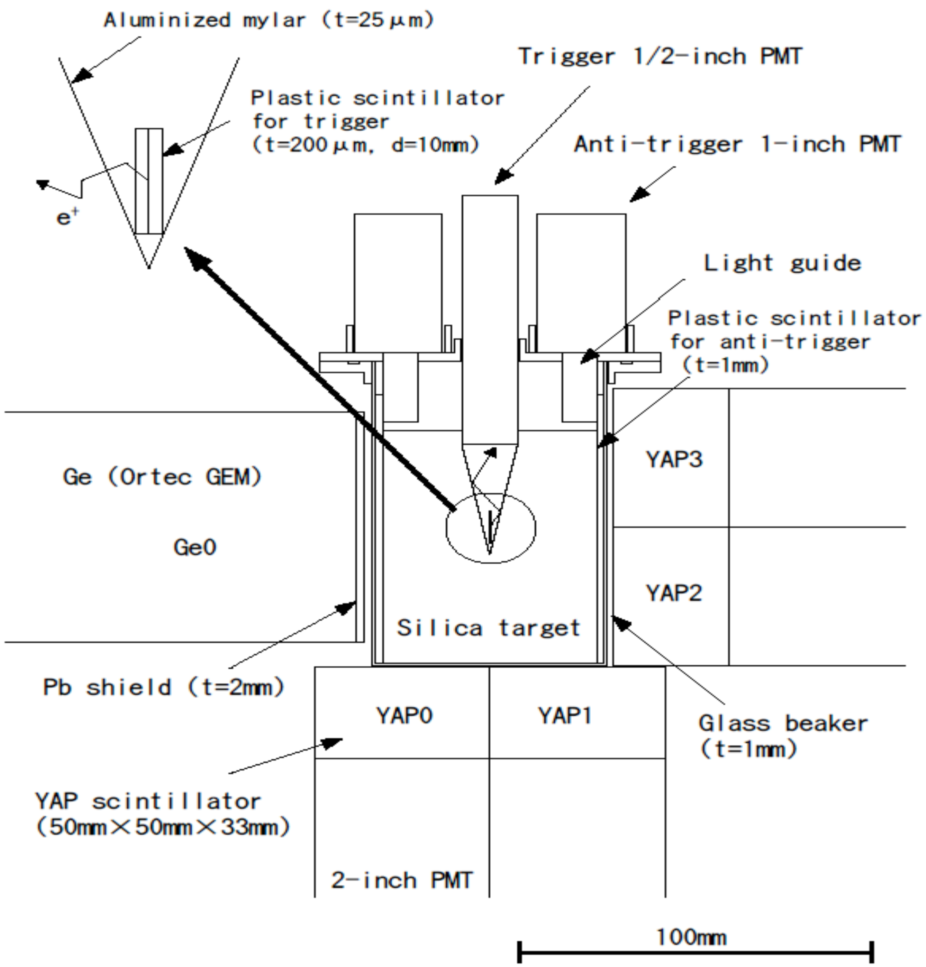
As density becomes lower,
→ elastic collision rate decreases
→ the non-thermalized o-Ps increases
→ $\lambda_{pickoff}$ becomes higher.

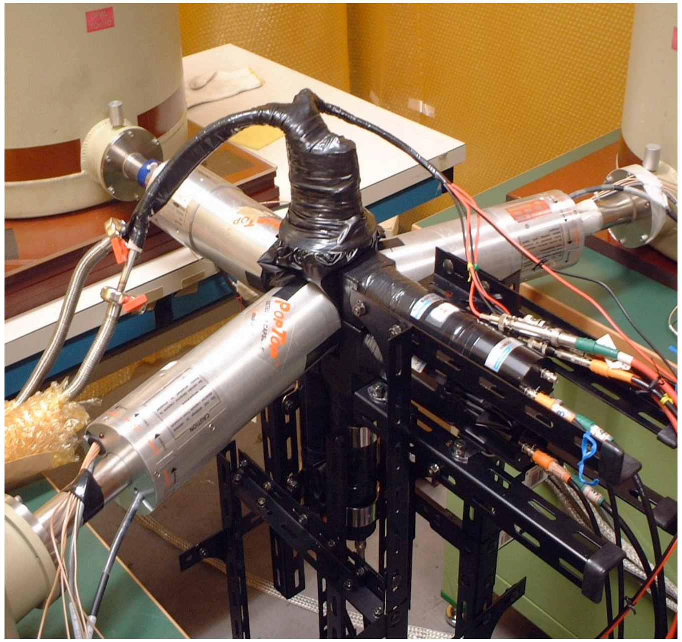
$$\lambda_{obs} = \lambda_{3\gamma} + \lambda_{pickoff}(t)$$

This was common/serious systematic error before 1995, it turns out that this make "o-Ps lifetime Puzzle"

Pickoff effect is a function of time(thermalize is taken into aacount), and $\lambda_{pickoff}(t)$ is directly measured using the energy spectrum.

[1] Setup





① Ps formation assembly

② YAP scintillator

is used to measure time spectrum

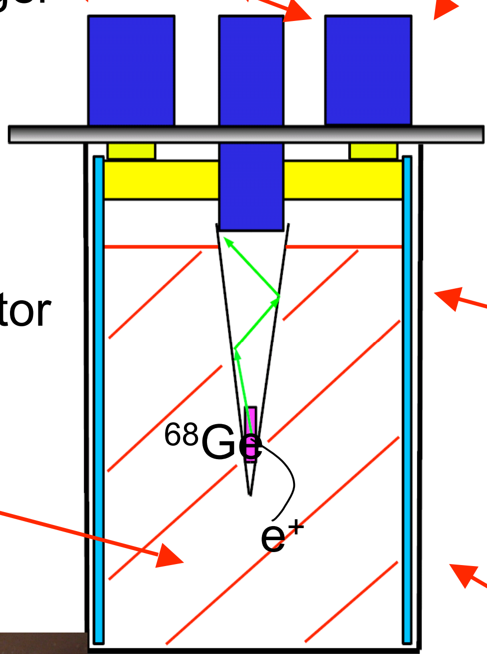
Time resolution σ=1ns (E>150keV)

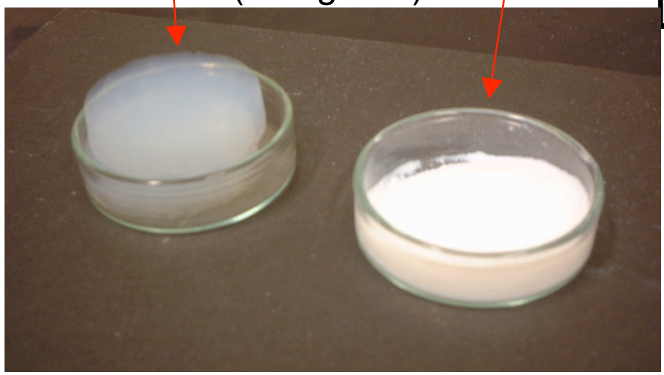
③ Ge semiconductor detecor

is use to measure pick-off

Energy resolution σ=0.5keV @511keV

Ps-Assembly





Anti-trigger is
used to select
the event
In which positron
stop in aerogel

Plastic scintillator for anti-trigger (1mm)

Vacuum vessel (glass 0.5mm)

YAP ($YAlO_3$:Ce) Scintillator

NaI and GSO are slow system and there is slow component, which makes pileup.

YLSO is fast, but this is radio active itself due to natural abundance ^{176}Lu

YAP($YAlO_3$:Ce) is used.

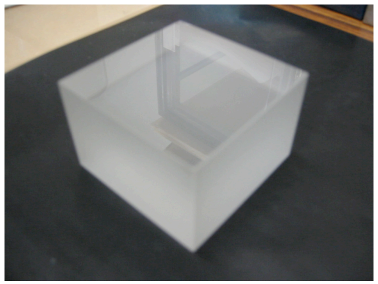
atomic number 39 <--- Small

density 5.37 g/cm^3

emision peak 370 nm

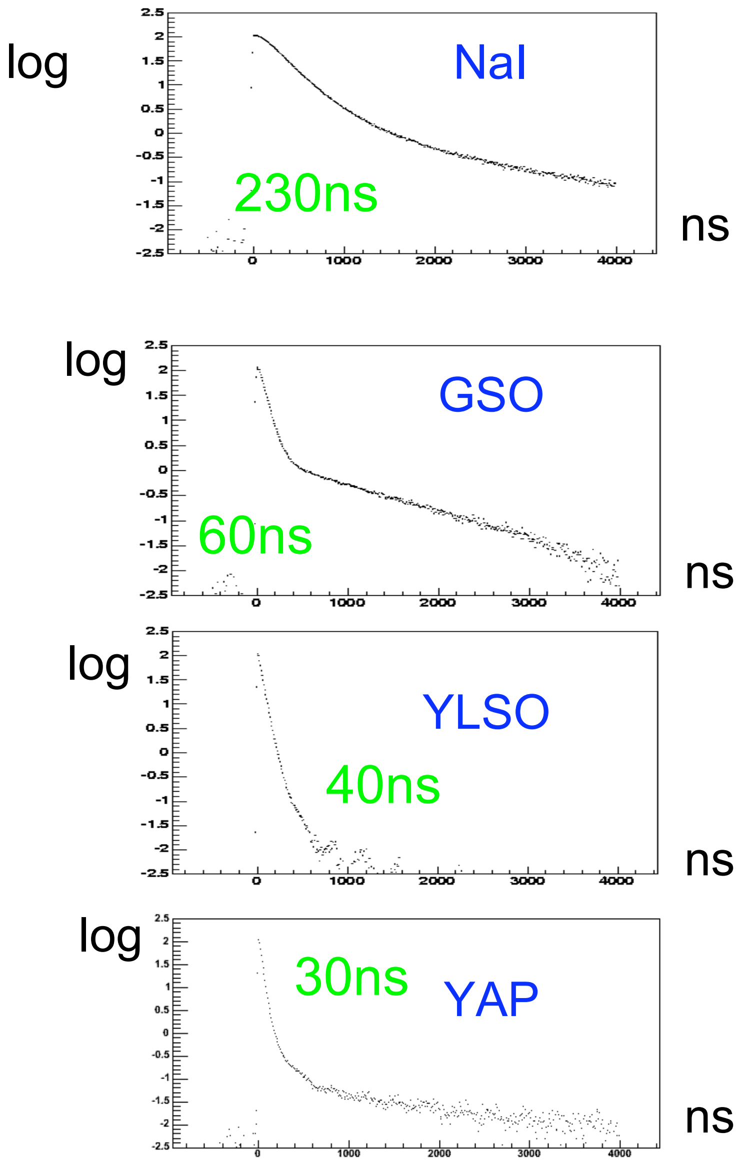
light output 40% of NaI (large yield)

decay constant 30 ns (small slow compo.)

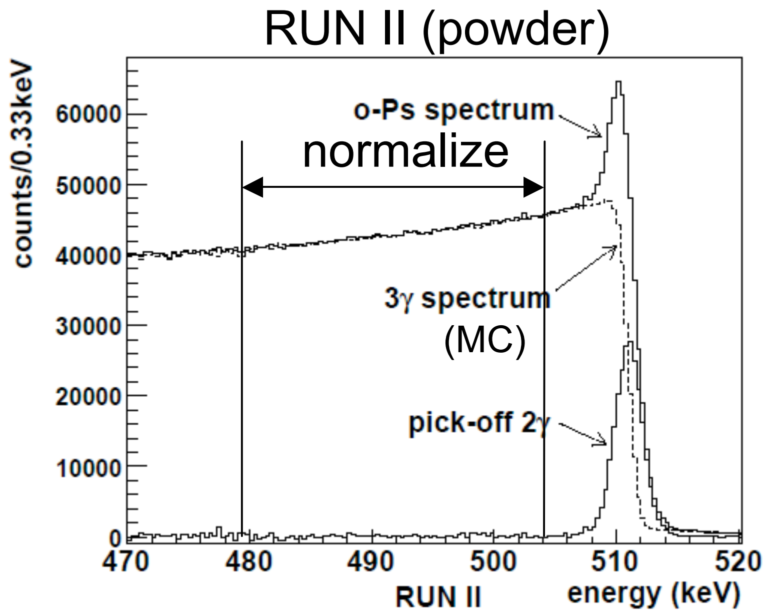


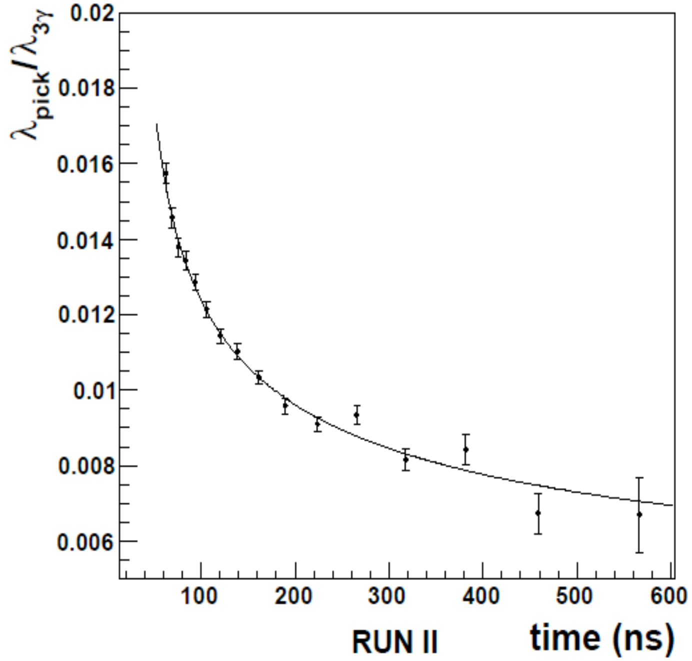
50*50*33mm crystal
We used 4 crystal

Pulse Shape recorded with FADC



[2] Pickoff ratio



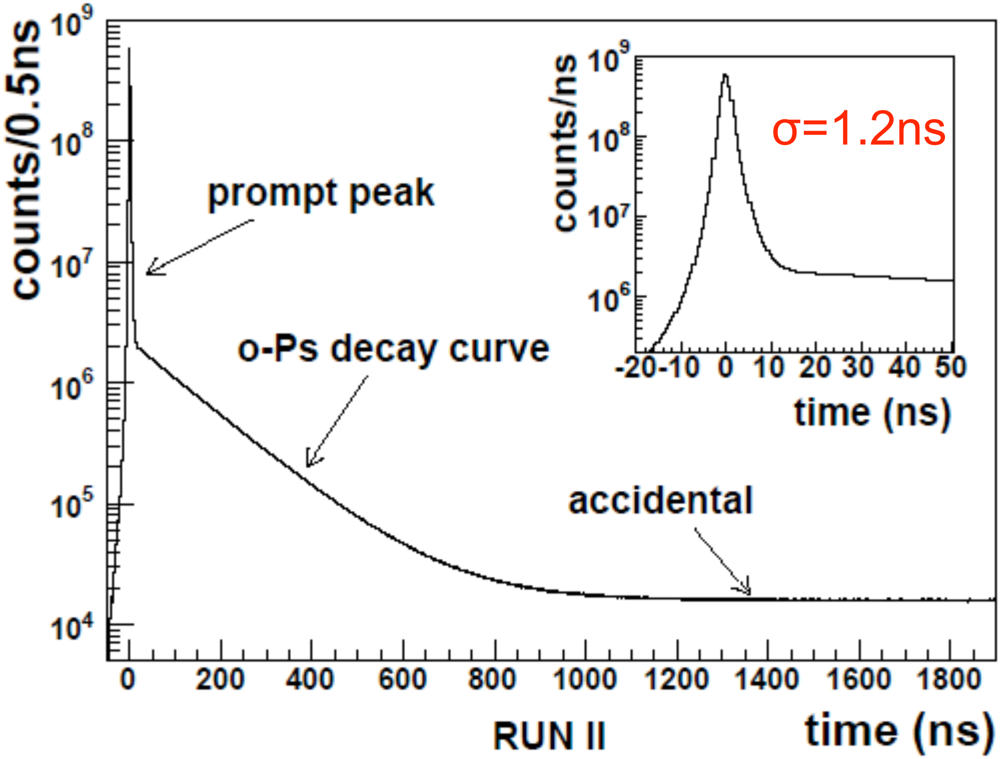


$\lambda_{pickoff}(t)/\lambda_{3\gamma}$

Energy spectrum of the γ
is measured by Ge semiconductor detector
* o-Ps →3γdecay is continuous spectrum
* Pickoff is 2γ decay and monochromatic
  peak is observed at 511keV
So we can separate the pickoff decay,
and $\lambda_{pickoff}(t)/\lambda_{3\gamma}$ is determined

It takes much time that
Ps thermalize well.
The non thermalized Ps was
the common/serious systematic
problem before 1995.

[3] Time spectrum



Time spectrum between β^+ emission and γ detection by YAP scintillator.

Good time resolution of 1.2nsec is obtained, and the clear o-Ps decay curve is observed. This is fitted with this function, in which the pickoff and thermalization process are taken into account automatically.

Fitting function：

$$N_{obs} = e^{-R_{stop}t}\left[\left(1+\frac{\varepsilon_{pick}}{\varepsilon_{3\gamma}}\frac{\lambda_{pick}(t)}{\lambda_{3\gamma}}\right)N_0\exp\left(-\lambda_{3\gamma}\int_0^t\left(1+\frac{\lambda_{pick}(t')}{\lambda_{3\gamma}}\right)dt'\right)+C\right]$$

Measured pick-off ratio is used.

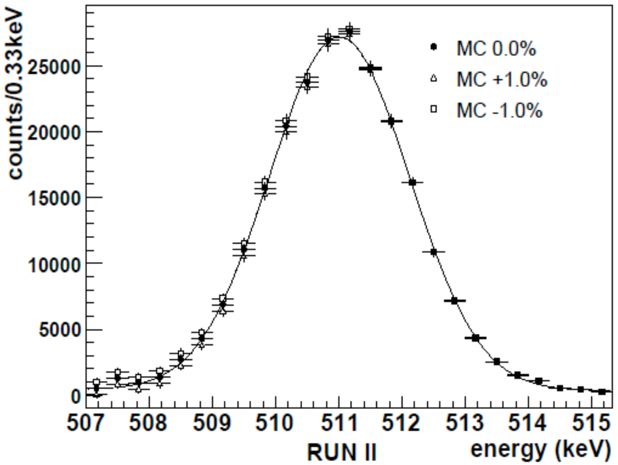
free parameters： N_0, $\lambda_{3\gamma}$, C

Decay rate can be obtained without extrapolation.

[4] Systematic errors

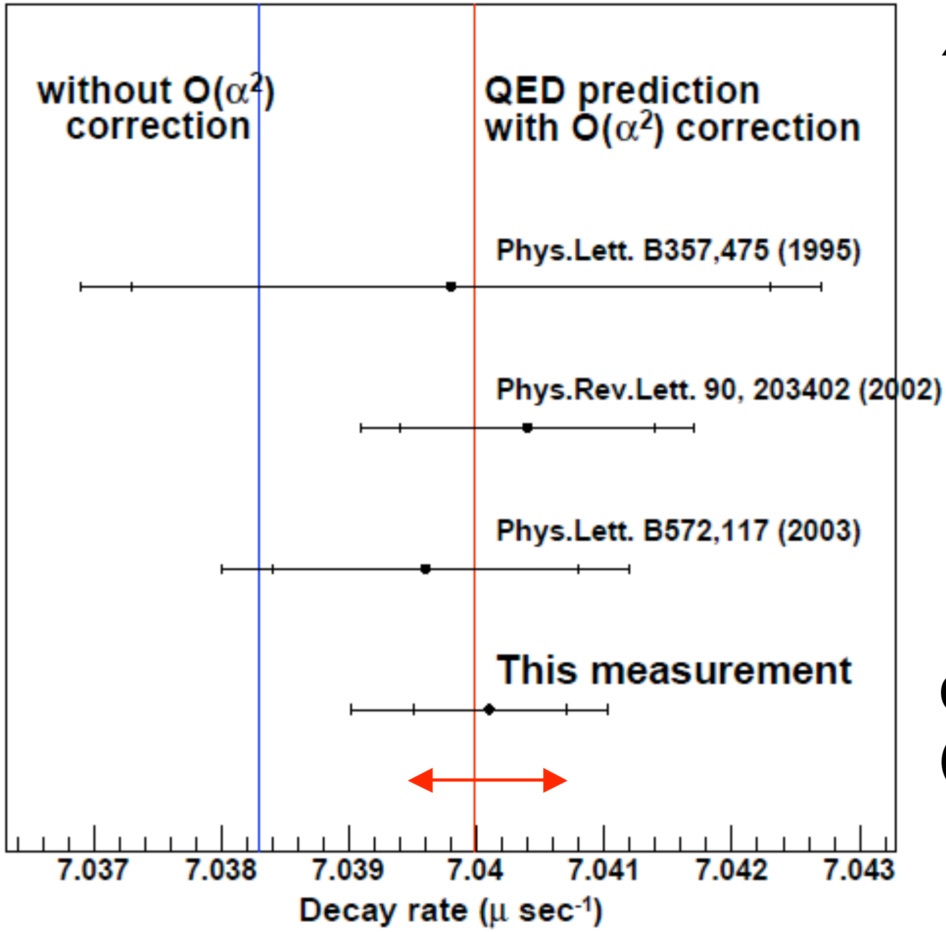
Source of the Contributions	For RUN I (*ppm*)	For RUN II (*ppm*)
TDC module related error		
– Integral Non Linearity	$< \pm 15$	$< \pm 15$
Contamination of pile-up events		
– for Base cut	$< +10$	$< +10$
Pick-off Correction		
– 3γ subtraction	± 89	± 91
– Ge detector efficiency	± 33	± 28
– YAP scintillator efficiency	± 64	± 19
Other Sources		
– Zeeman effect	-5	-5
– Three-photon annihilation	-91	-33
– Stark effect	-3	-4
Total	-147 and $+116$	-104 and $+99$

Main systematic error comes from the 3γ-2γ separation:



Uncertainty of the normalization of 3γ contribution is about 1% and it is origin of the error. This uncertainty makes asymmetry of the obtained pickoff spectrum, and we can check this distribution with the reference (measured with 514keV monochromatic γ)

[5] Result



The result is

$$\lambda_{o-Ps} = 7.0401 \pm 0.0006(stat.)^{+0.0007}_{-0.0009}(sys.)\ \mu s^{-1}$$

(total error 150ppm)

This shows the history of the measured decay rate after 1995. Red/blue lines show $O(\alpha^2)$ and $O(\alpha)$ calculation, respectively. This result is most accurate and consistent with last three 3 results.

Combined value of these 4 results (common systematic of our method)

$$\lambda_{o-Ps} = 7.0401 \pm 0.0007(total.)\ \mu s^{-1}$$

consistent with $O(\alpha^2)$ calculation and differs from $O(\alpha)$ by 2.6σ

This is first test of $O(\alpha^2)$ for the o-Ps decay rate

[2] Hyper Fine Splitting

[1] Principal of the HFS measurement(the old method):

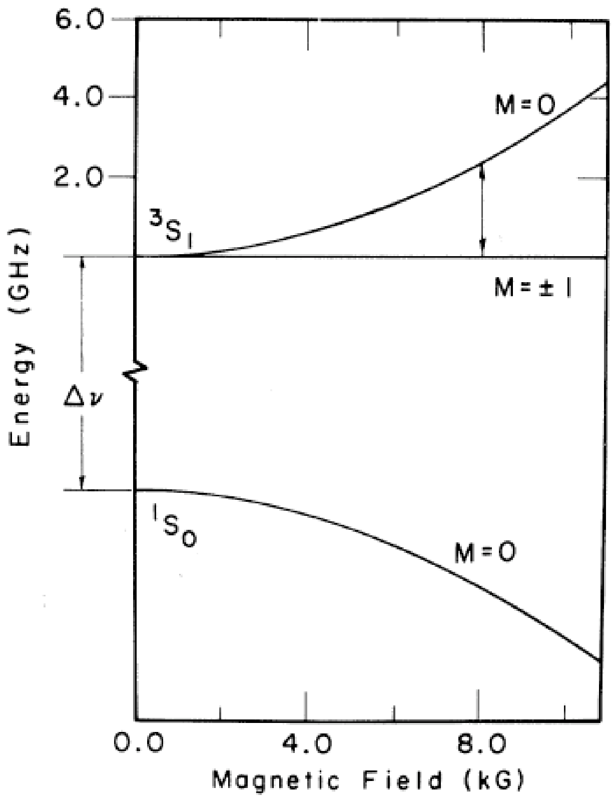
$$\tilde{\mathcal{H}}_0 = \begin{pmatrix} E_1 - i\hbar\gamma_1 & & & \\ & E_1 - i\hbar\gamma_1 & & \\ & & E_1 - i\hbar\gamma_1 & \\ & & & E_0 - i\hbar\gamma_0 \end{pmatrix} + g'\mu_B B_0 \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 0 & 1 \\ & & 1 & 0 \end{pmatrix}$$

In the static magnetic filed, the states of (S=1 M=0) and S=0 are mixed (Zeeman effect). The energy shift of the new state

$$\Delta E' = \frac{1}{2}\Delta\left[\sqrt{1+x^2} - 1\right]$$

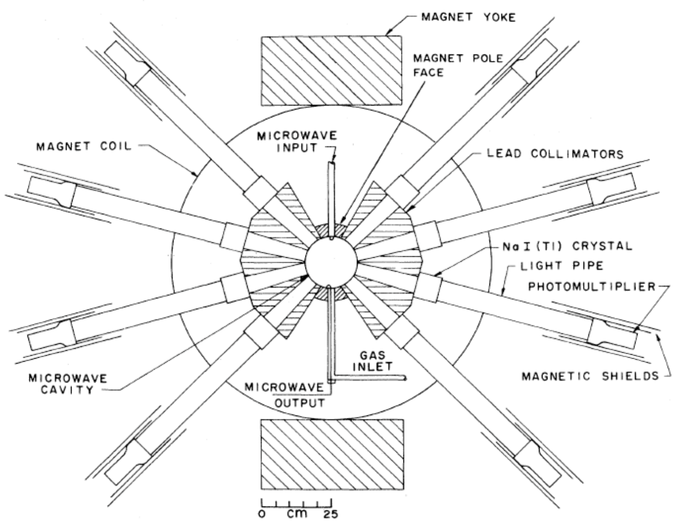
$$x = 2g\mu_0 H_0 / \Delta$$

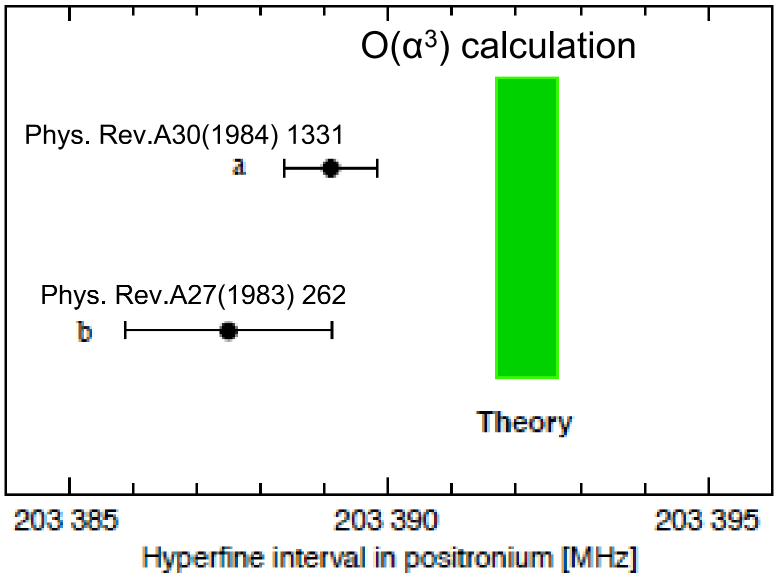
is proportional to the HFS



The Zeeman shift(ΔE') is measured with microwave(GHz), and interpreted into HFS(Δ) with the yield of the static magnetic field.

Set up in Phys. Rev. A30 1331





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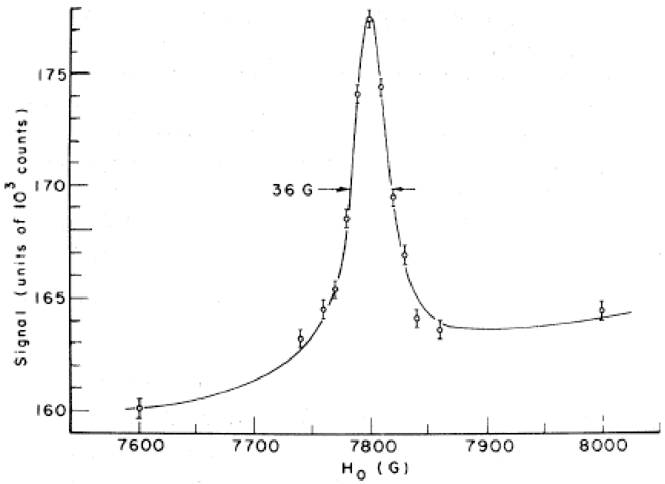
2.3GHz RF is stored in Cavity and the static magnetic field are applied and scanned.

o-Ps(M=±1) -> S=1 M=0 -> S=0 -> 2γ

Number of back-to-back 2γ event increase at resonance:



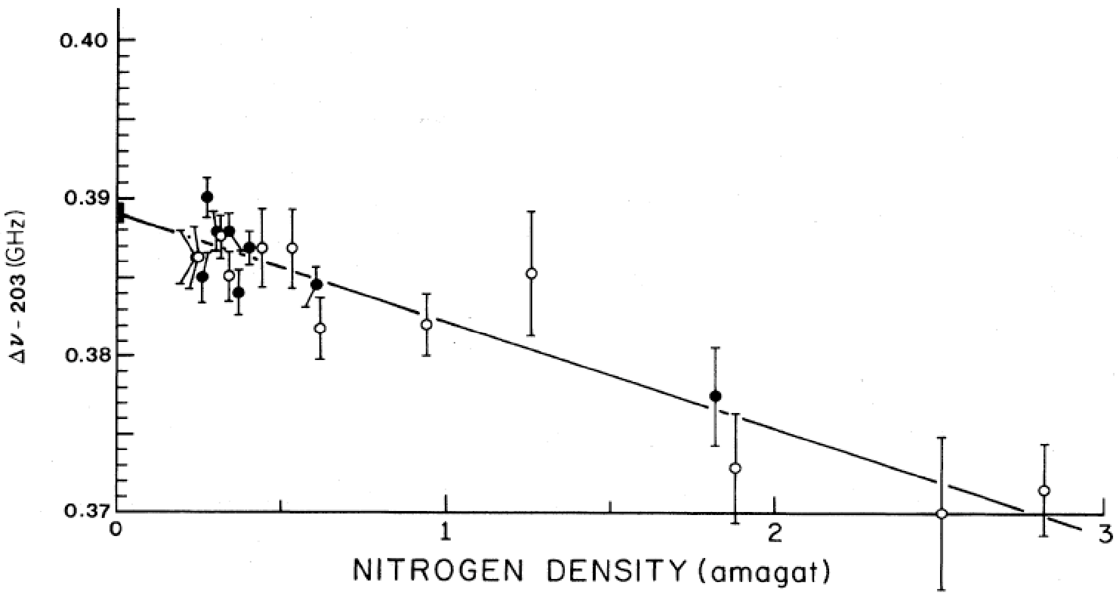
As I have already mentioned, the theoretical calculation is improved recently,

3.5σ discrepancy is observed.

[2] Systematic problems in the old methods:

(1) Material effect and non-thermalized o-Ps

As the same as the measurements of o-Ps decay rate, material(gas) is used to make Ps, and the produced Ps collides these material. Close to the material, the Ps feels the electric filed produced with the material, and the energy-level shifts due to Stark effect(10ppm order). This material should be corrected, and the same extrapolation method was used.



Changing density, the measurements are performed and extrapolate to zero density.

But as the same as decay rate measurements, there is systematic problem of the unthermalized o-Ps.

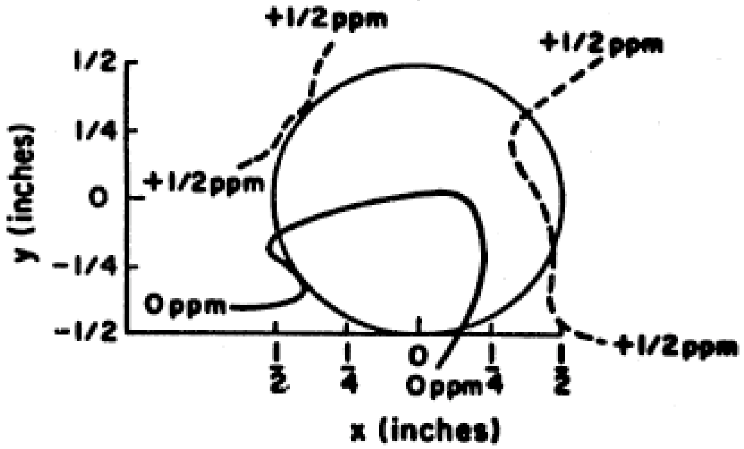
[2] uniformity of the magnetic field.

Uncertainty of the magnetic field makes the systematic error on the HFS directly. Since o-Ps decay space is widely spread in cavity, the uncertainty of uniformity of the magnetic field is crucial.

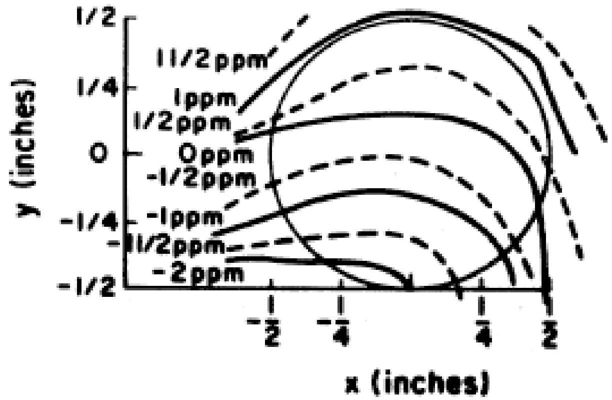
Right figures show the shift of the magnetic Field and look complicated,this was significant systematic error in the previous measurement.

Large Volume and accurate magnetic filed are developed recently for NMR.

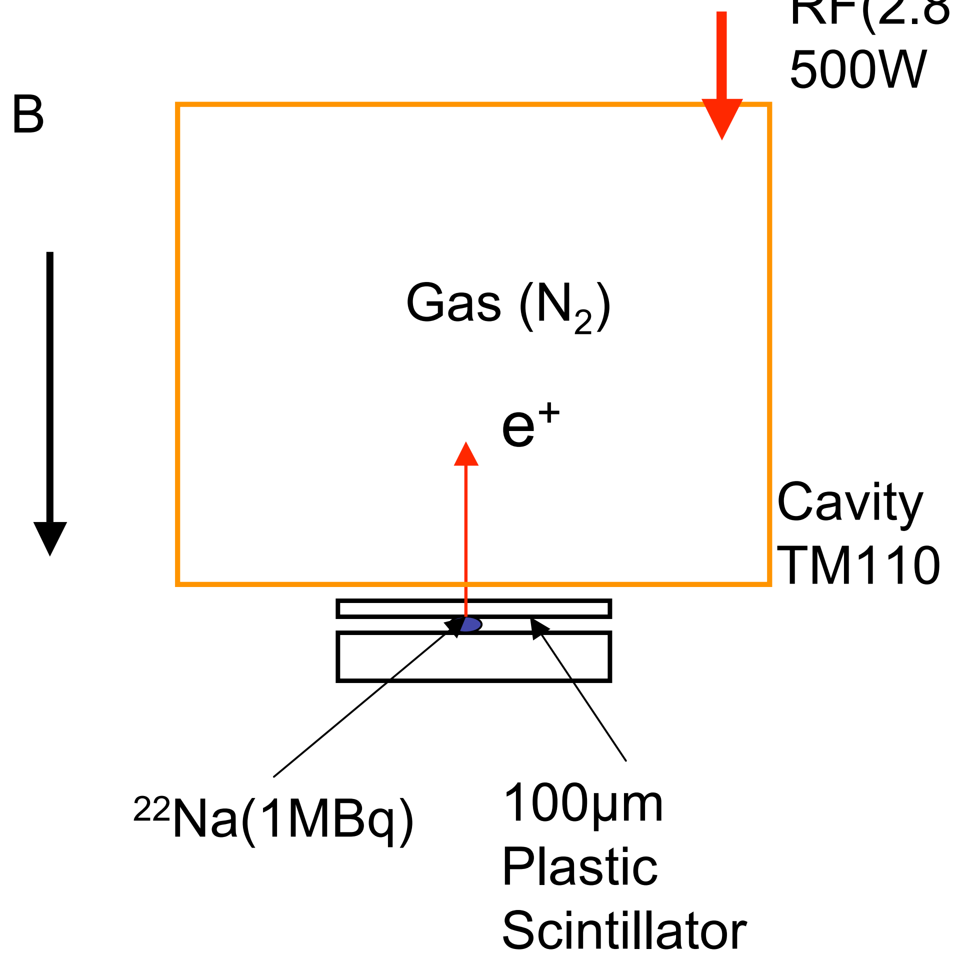
$z = 0''$ plane



$z = -\frac{1}{2}''$ plane



[3] Our New method(s): (1) Conventional Zeeman



^{22}Na β source (1MBq) is used, e^+ pass through thin plastic scintillator, making trigger signal. Positron stops in Gas, N_2 0.5-2 atm, and makes Ps.
High power 500W RF (2.8GHz) are stored in Cavity (TM110):

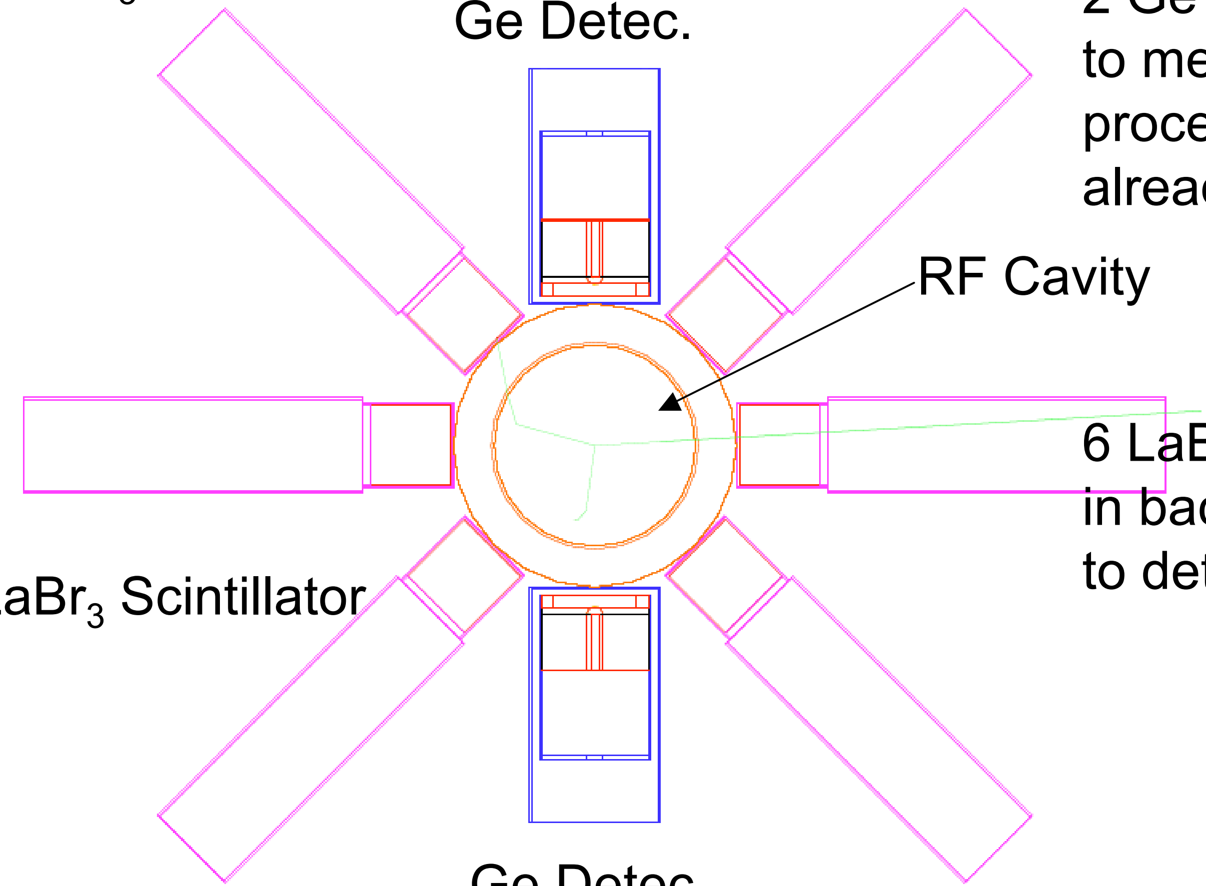
High static magnetic field is applied:
(Not yet decided, but we will discuss with KEK next Monday: the magnet system has large bore, high accuracy, developed for the medical NMR.)

Our new method to determine t=0, at which Ps forms.

γ detectors:

The RF cavity are covered by 8 γ-detectors:

2 Ge detectors are used to measure thermalization processes, this method is already well established.



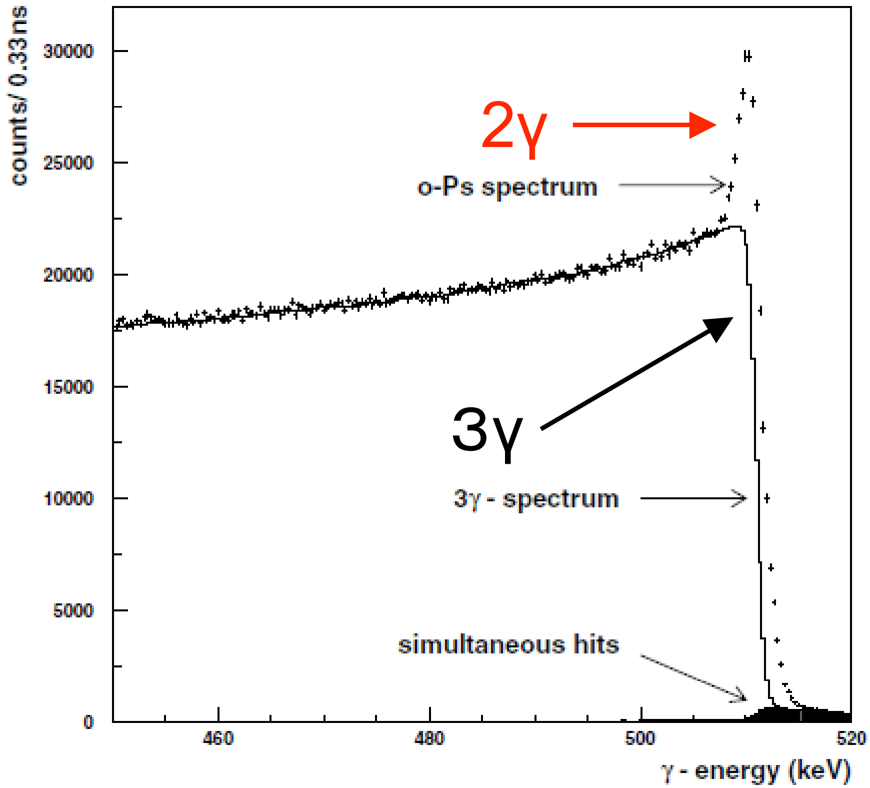
6 LaBr$_3$ detectors are set in back-to-pack position to detect 2γ decay.

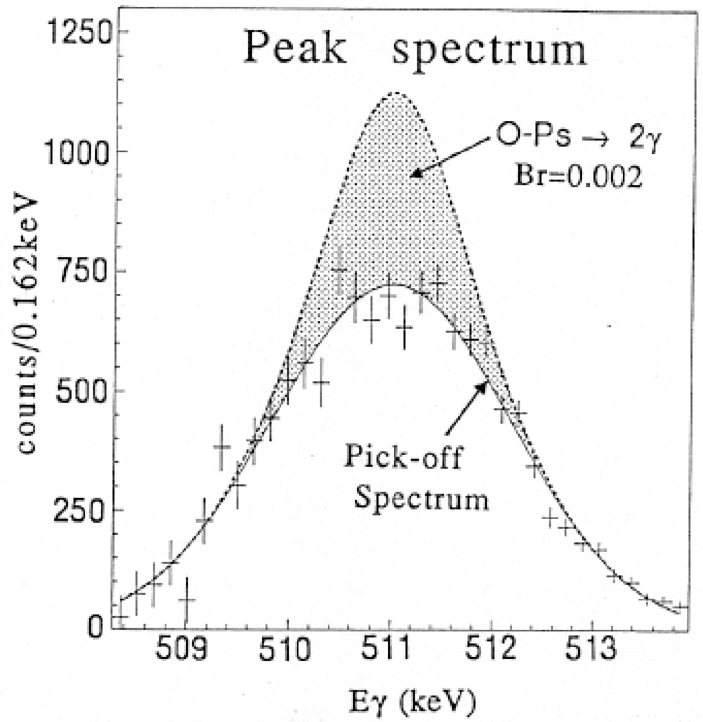
Ge semiconductor detector:

We can measure precise energy spectrum as a function of time

(1) thermalization processes can be measured: (二匹目のどじょう)

(2) We have good chance to separate Zeeman resonance from pickoff annihilation: (Due to Fermi motion: pickoff spectrum has wide width. 2.6keV.)

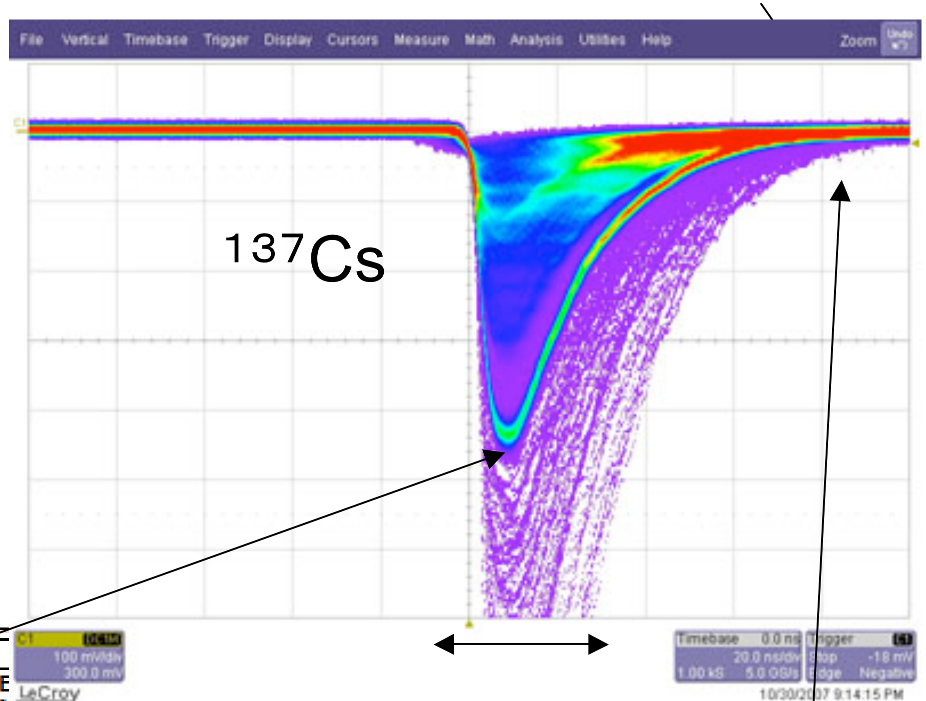




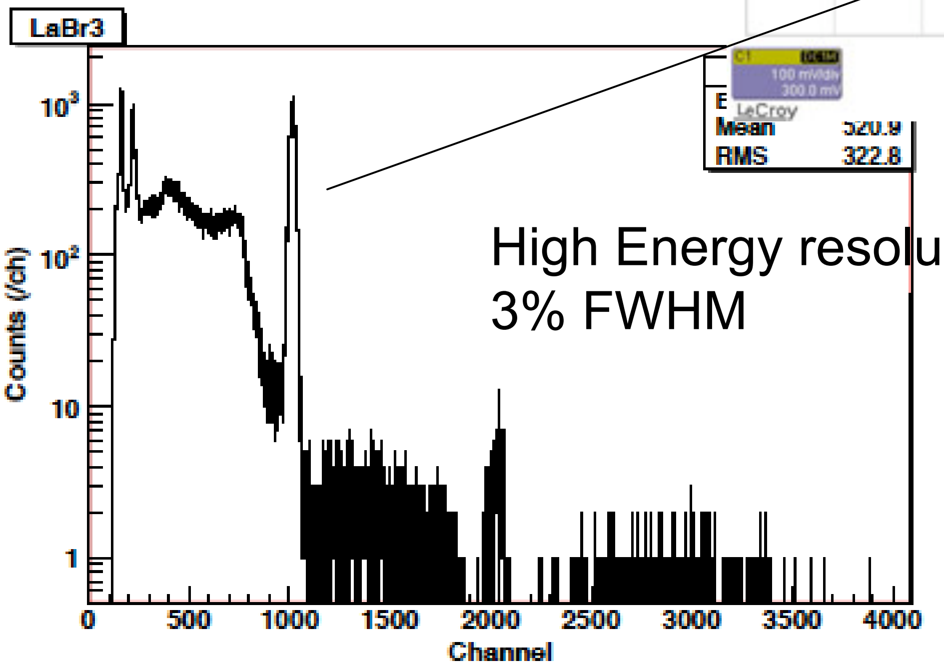
These data are our old data, not with this setup

$LaBr_3$ Scintillator

D=2inch will be used



^{137}Cs



40nsec Fast

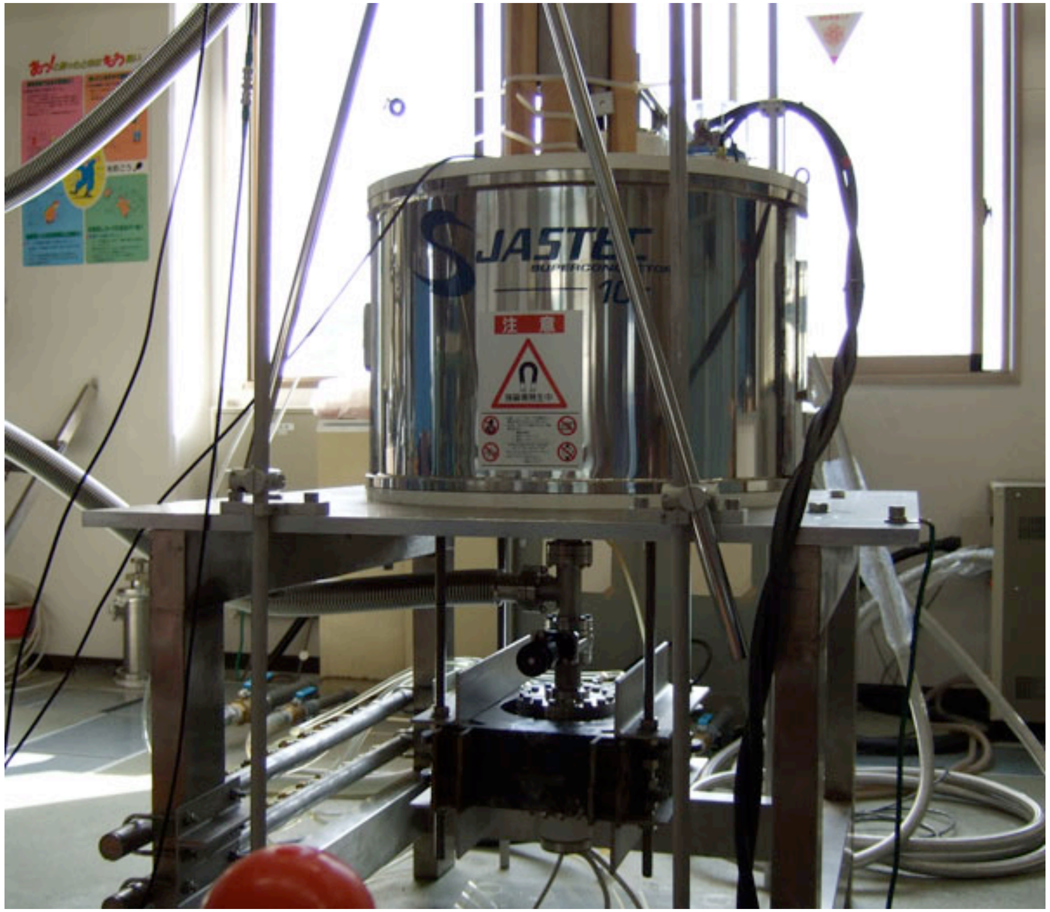
High Energy resolution
3% FWHM

No slow component
We can use strong source

511-511KeV 2γ decay can be tagged with energy information

[4] Our New method(s): (2)203GHz direct transition

Prof. Idehara(U. Fukui) are developing GYROTRON which provides powerful and high frequency RF source:

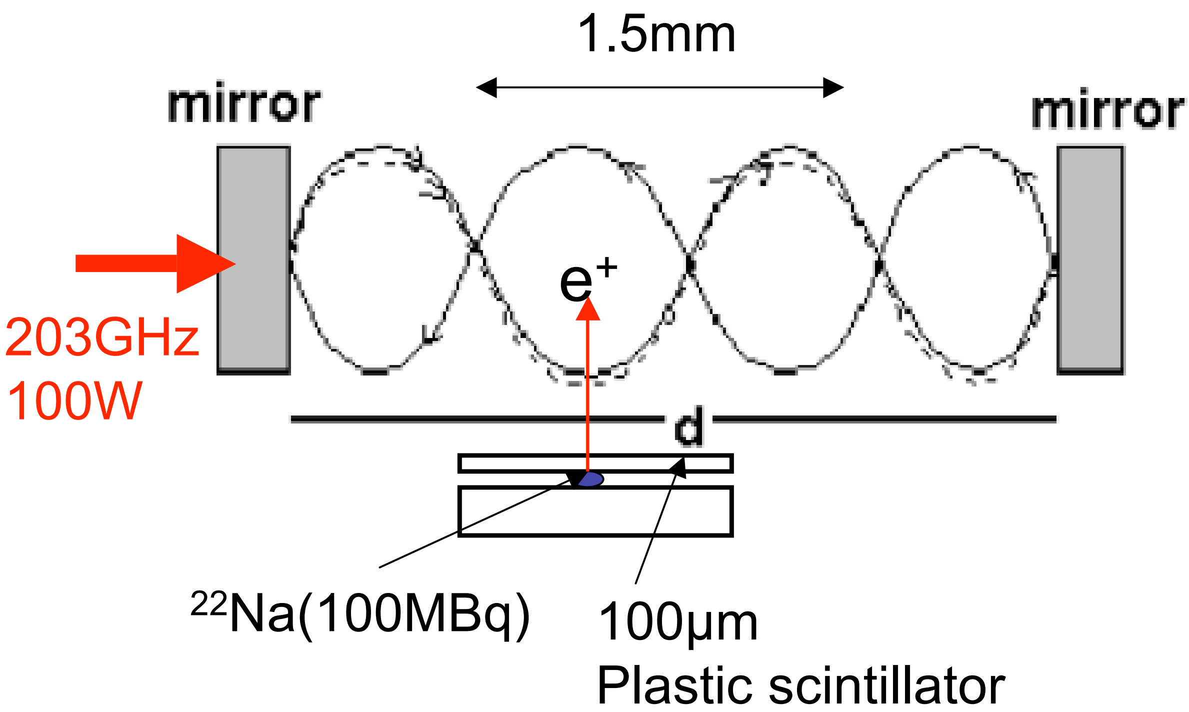


Power > 100 W
Frequency 203+-1GHz
stable < 1-10 ppm
CW

Tunable frequency-system and high stability are new challenge of the GYROTRON.

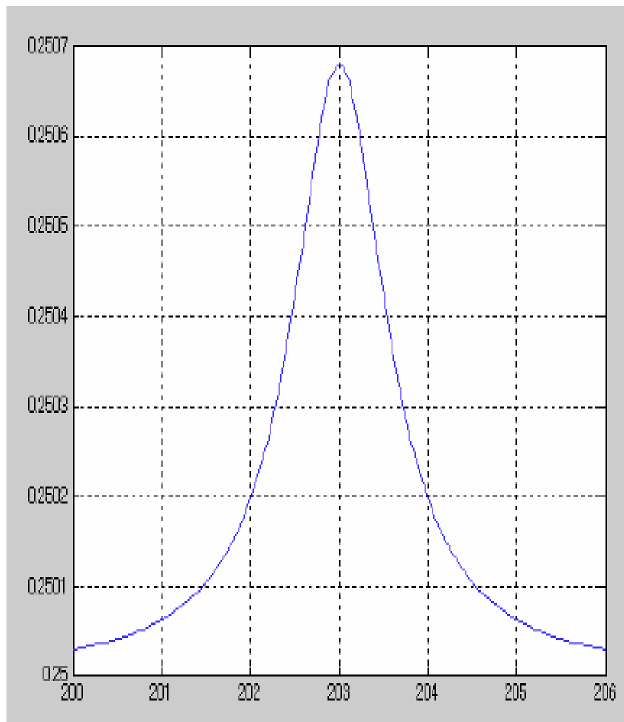
Test system of GYROTRON

Central Ps assembly is formed with
203GHz Fabry-Perot type Cavity (not yet designed)

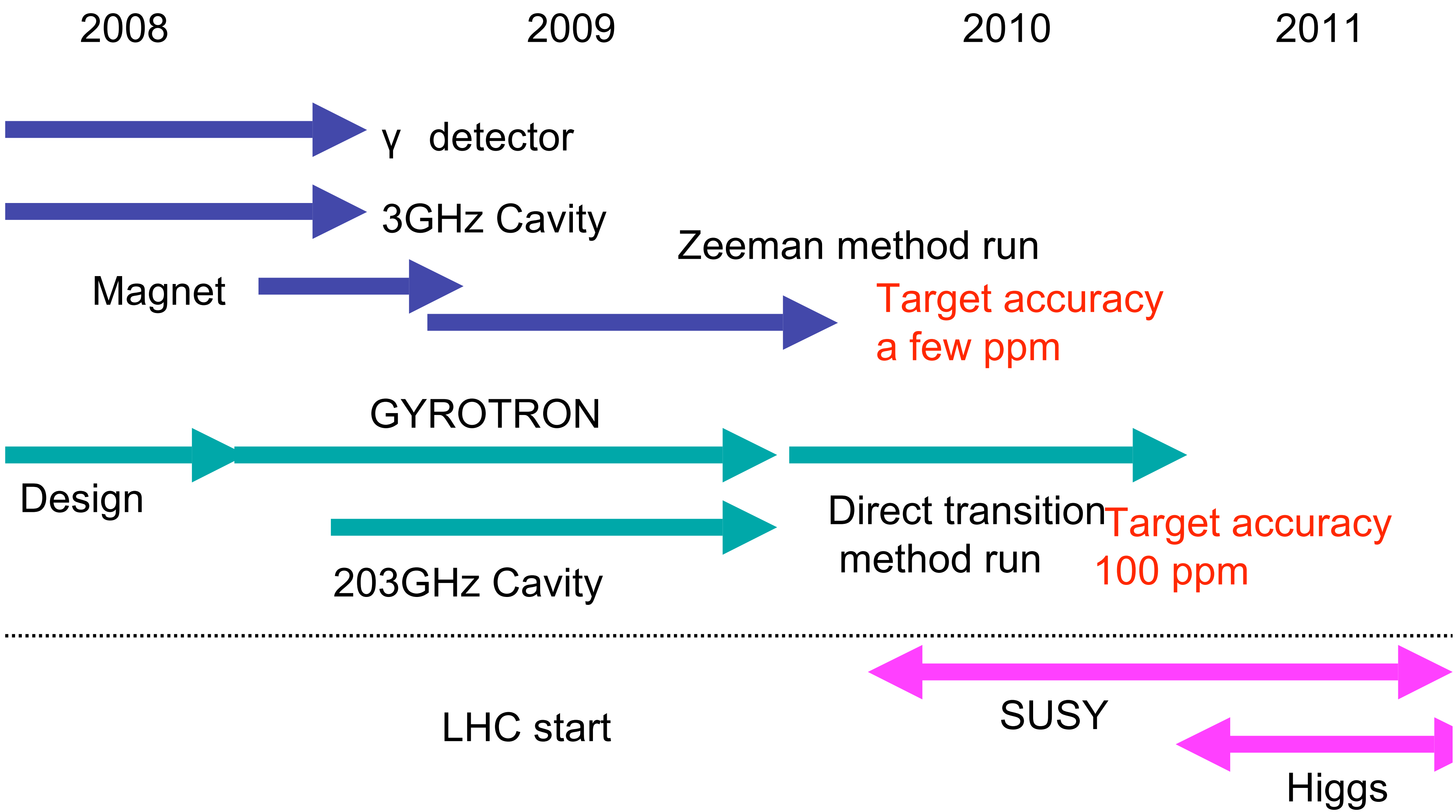


γ detector are the same, no static magnetic field is applied.

Changing RF 203+-1GHz,
We can measure the resonance, directly.
First observation of “mm wave” transition.
FWHM=0.63GHz, which is determined by p-Ps lifetime



[5] Time schedule



Conclusion

(1) Precise measurement(150ppm) of the o-Ps decay rate has been performed and we obtained:

$$\lambda_{o-Ps} = 7.0401 \pm 0.0006(stat.)^{+0.0007}_{-0.0009}(sys.)\ \mu s^{-1}$$

This result is consistent with the last three measurements, and the combined value is

$$\lambda_{o-Ps} = 7.0401 \pm 0.0007(total.)\ \mu s^{-1}$$

It is consistent with $O(\alpha^2)$ calculation and differs from $O(\alpha)$ by 2.7σ

(2) 3.5σ deviation was found out in Hyper Fine Splitting from $O(\alpha^3)$ calculation.

There are two possible systematic errors in the previous measurements (Thermalization and Magnet uniformity)

We propose new measurements overcoming them.

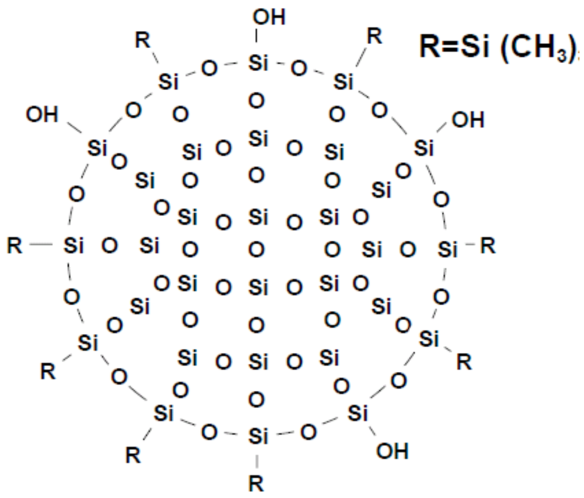
•Stark Shift

We know the charge distribution of the power and aerogel:

$\lambda_{3\gamma} \propto$ Flux Factor $\propto$ $|\psi(r=0)|^2$

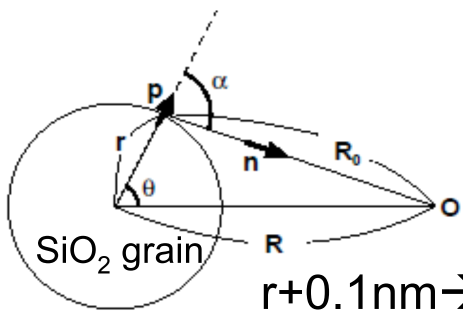
$$\frac{\Delta\lambda_{3\gamma}}{\lambda_{3\gamma}} = E^2 \frac{|\varphi_1|^2}{|\varphi_0|^2} = 248 \cdot \left(\frac{E}{E_0}\right)^2$$

$$(E_0 = 5.14\times10^9 V/cm)$$



1. Charge
   3×10^{-9} C/g(measured)
   1×10^{-7}ppm very small effect

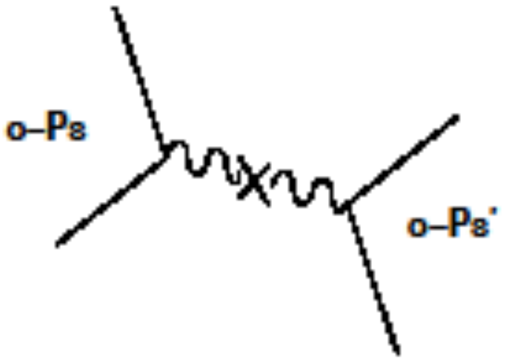
2. dipole moment (Si-OH)
   p=1.7×10^{-18} esu･cm
   density of dipole OH 0.44/nm^2
   dipole filed → 3ppm



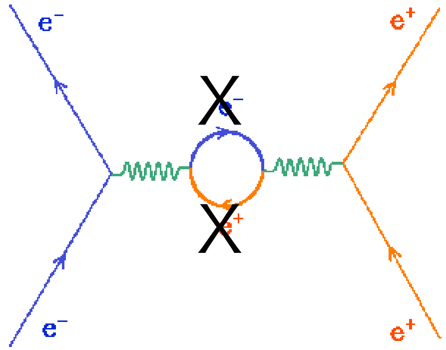
r+0.1nm→300nm

Both can be smaller than accuracy of decay rate measurements:
and consistent with the material correction on the HSF measurement.

素粒子物理としてo-Psだけ効く「真空振動(87GHz)」がとくに面白い。(ズレは、これらnew Physics の信号の可能性？)



•未知の重い粒子のループ効果



•未知の軽く、相互作用の極めて弱い反応の粒子の効果
axion, Milichargedなど
•余剰次元の効果があると、この状態は影響を受ける