Application of Gyrotron: Precision measurement of Positronium HFS

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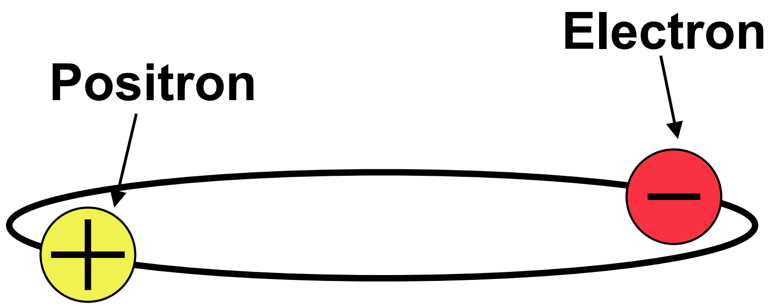
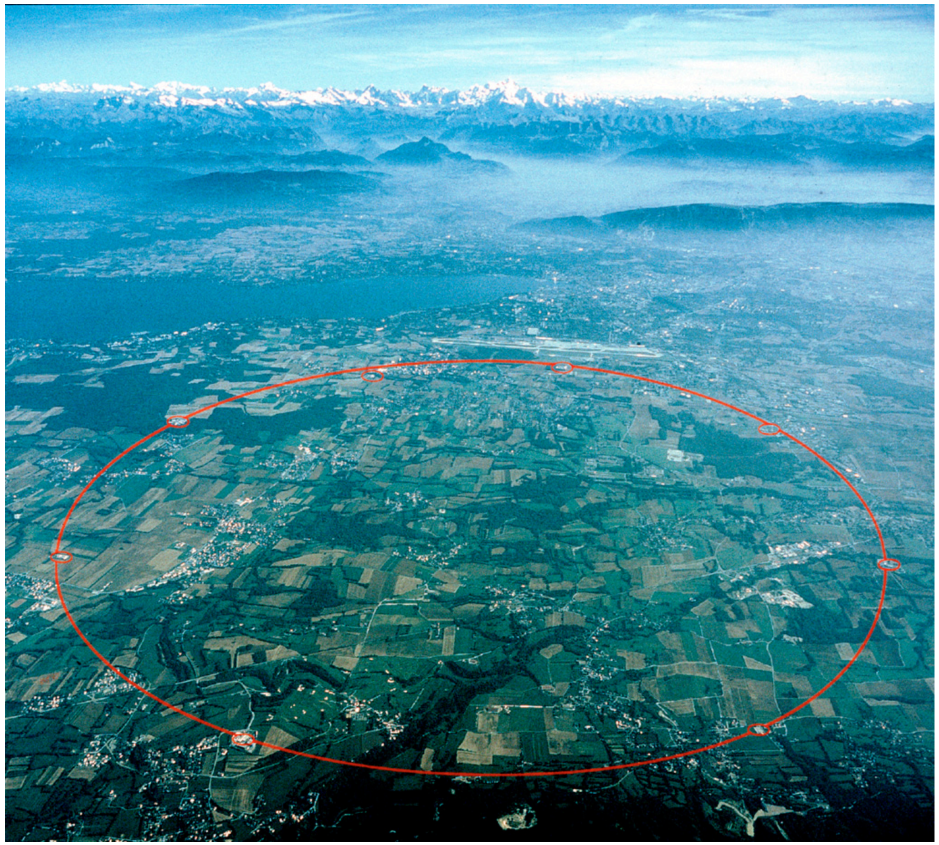
Positronium: Ps

Ps is the bound state of e^+ and e^-, and the "**lightest atom**". Ps is a clean and excellent target to study "**QED**", since it is free from the hadronic uncert. Furthermore Ps is particle- antiparticle system, interesting for high energy physicist. (e+e- collider !!)





Lowest ECM e^+e^- collider： Ps
ECM=1022keV-6.8eV（bind.)
D=$2a_0$~1Å

Highest ECM e^+e^- collider: LEP
ECM=209GeV 10^5 higher
D=8.6 km
(LEP -> LHC now under operation)

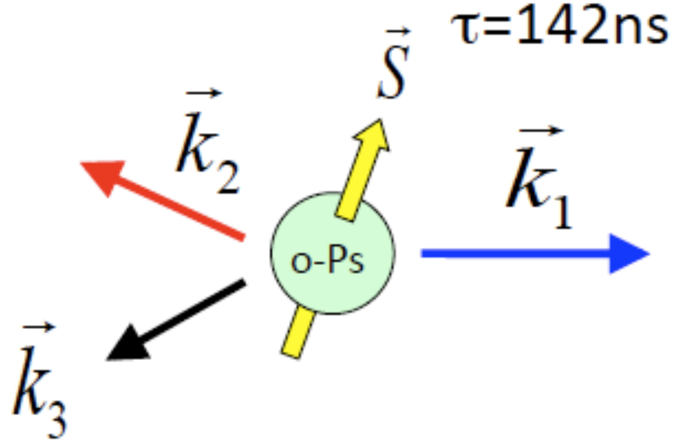
Positronium: Ps

Ps is classed to two state (spin parallel and anti-parallel)

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

o-Ps $\rightarrow$ 3γ、(5γ,..)

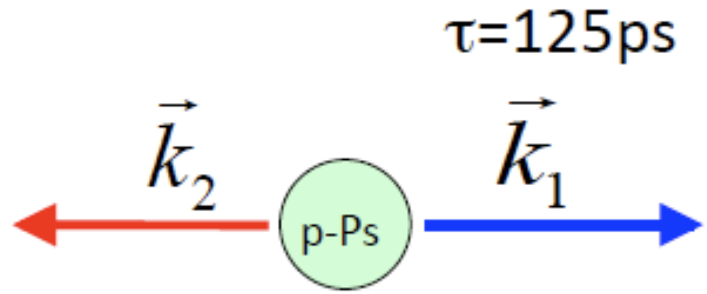
Long lifetime τ=142nsec



=0 (Singlet)   parapositronium (p-Ps)

p-Ps $\rightarrow$ 2γ、(4γ, …)

Short lifetime τ=125psec

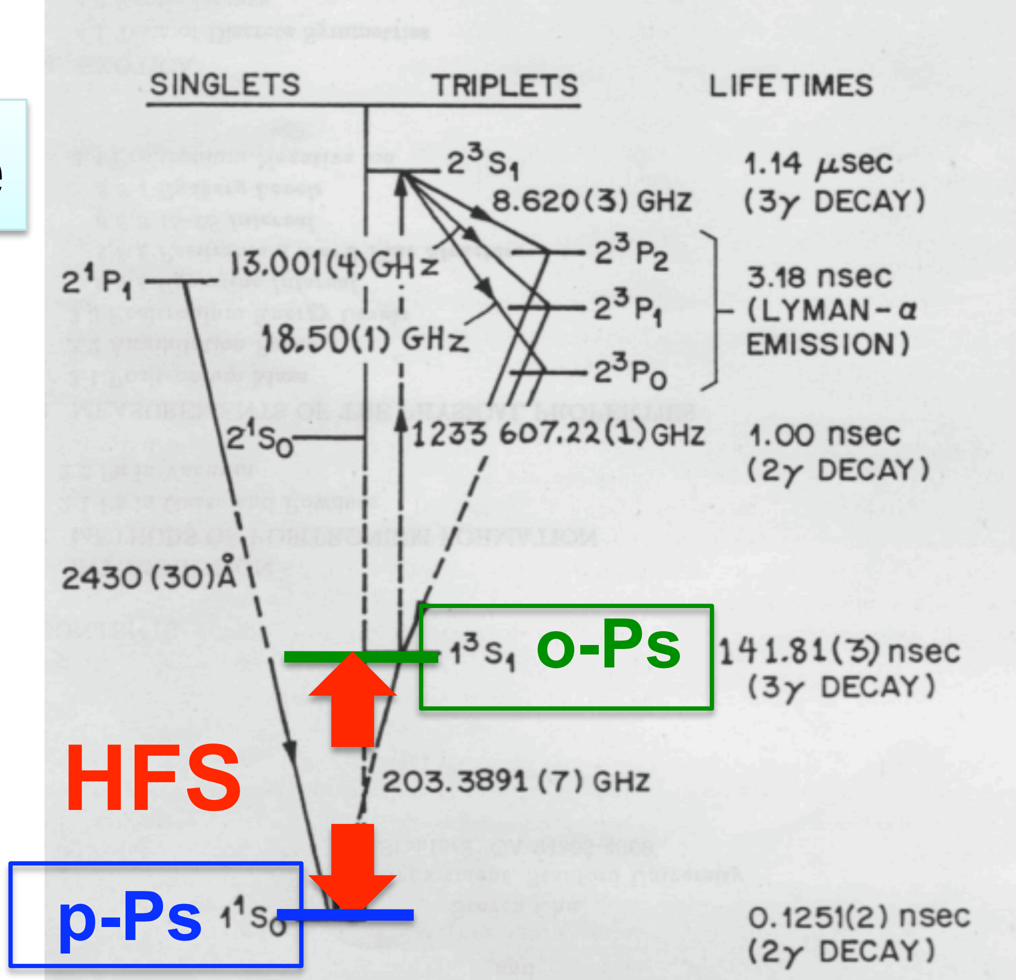


Photon C=(-1) for charge conjugation, while C=-(-1)$^{S+1}$ for e+e- system.

Higher multiplicity decay is suppressedby 10^{-6} so only 3 and 2 γ decay is enough for study.

Energy level of Ps state

Energy split between p-Ps and o-Ps "HFS" is about 203GHz, which is much larger than H-atom(1.4GHz)



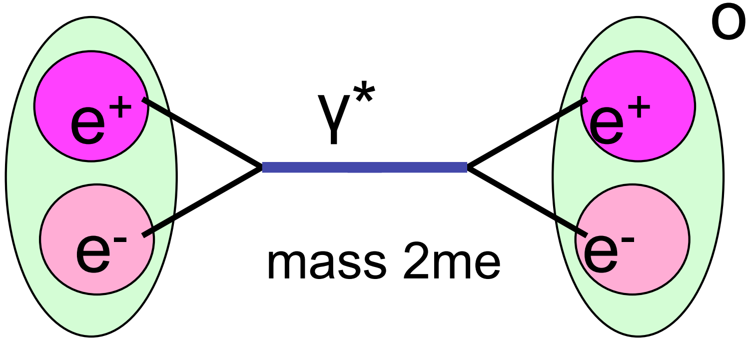
(1) Since magnetic moment of $e^{\pm}$ is large, then the spin-spin interaction has a large contribution,

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

(2) o-Ps has the same quantum numbers as photon. So o-Ps is always fluctuates (Frequency 87GHz.)

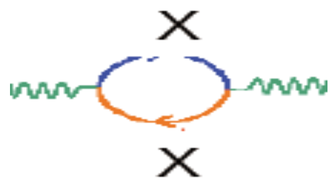
o-Ps

87GHz

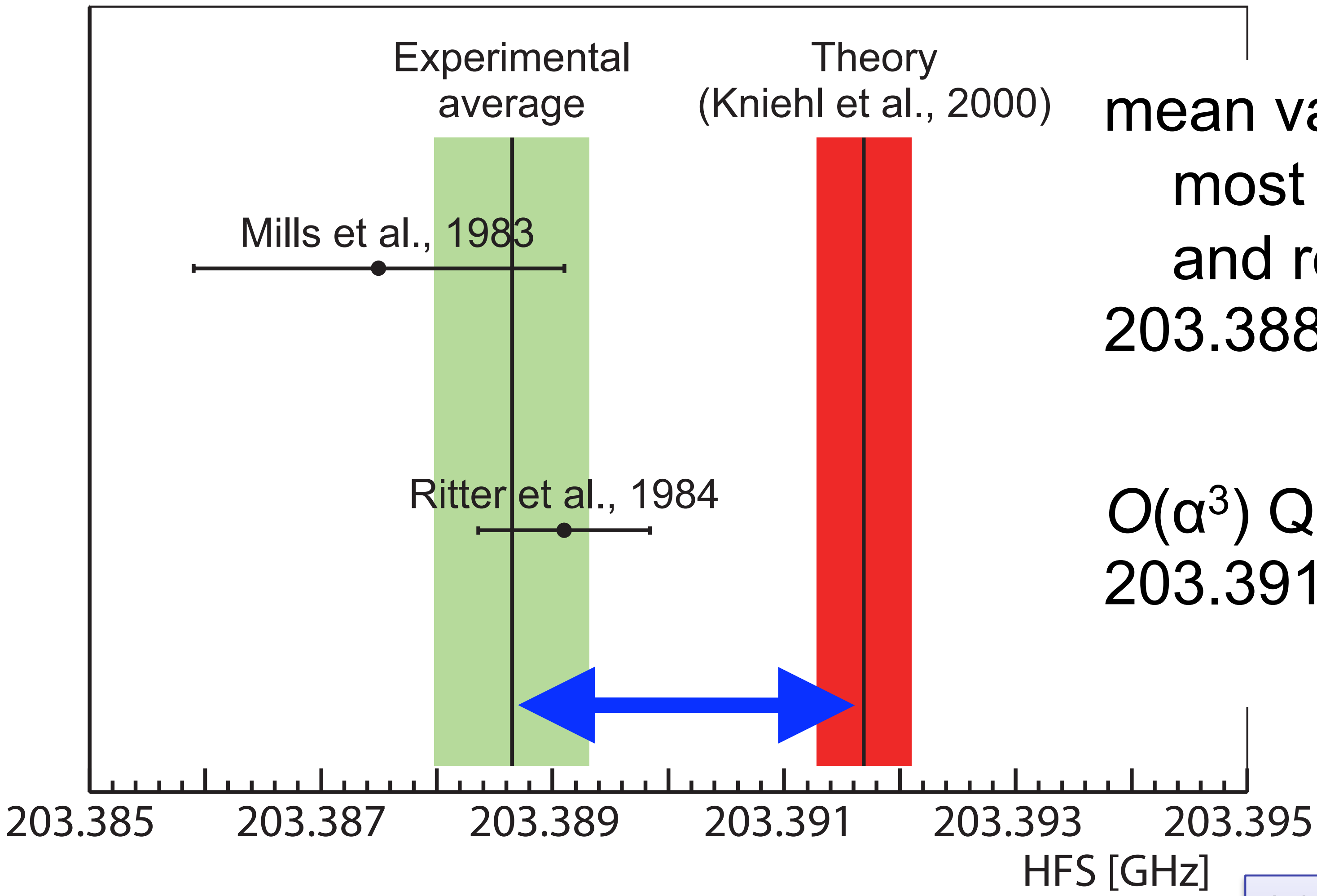


o-Ps

A new physics (beyond SM) contributes on the propagator.



QED is not “old” “well-established” theory for the bound-state.
The $O(\alpha^3)$ corrections have been calculated with the new method in 21st.



HFS

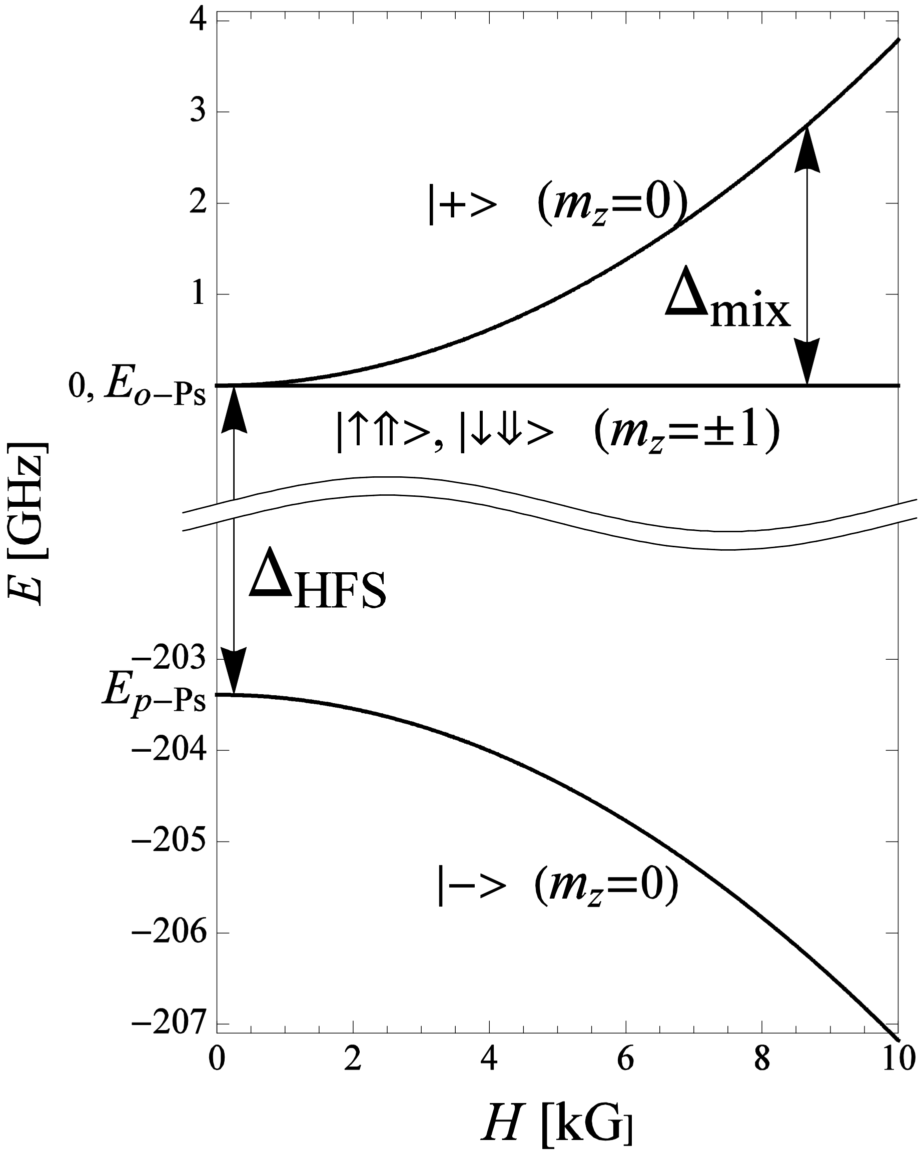
mean value of the most precise and recent results
203.388 65(67) GHz
(3.3 ppm)

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

There is large discrepancy between the measured and the QED prediction by **3.9σ (15ppm)**

(1) QED crisis?
(2) New physics contrib.?
(3) wrong experiment?

Principal of the OLD experiments (Previous all experiments):



Indirect method was used

In the static magnetic fleld,
the states of (S=1 mz=0) and S=0
are mixed (Zeeman effect).
The Zeeman shift is proportional to
the HFS and H^2 (approx. x <<1)

$$\Delta_{mix} = \frac{1}{2}\Delta_{HFS}\left[\sqrt{1+x^2}-1\right]$$

$$x = 2g\mu_0 H_0 / \Delta_{HFS}$$

The Zeeman shift(Δ_{mix}) were measured with microwave(~3GHz), and interpreted into HFS(Δ_{HFS}) with the yield of the static magnetic field(~8kGauss).

There are two systematic errors in the old indirect method

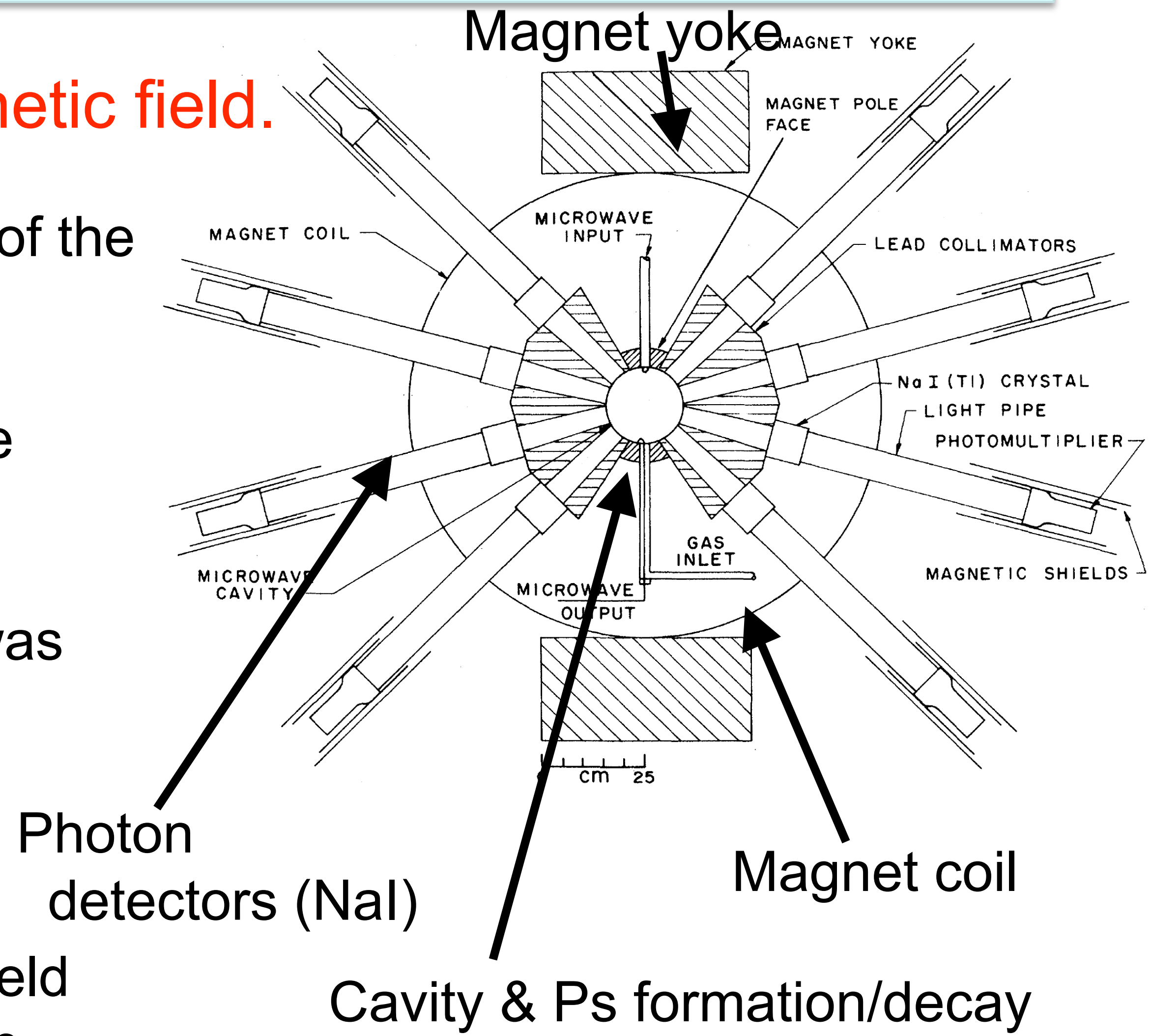
[1] uniformity of the magnetic field.

This figures shows the setup of the previous experiment.

Ps formed and decayed in the cavity wide space O(~10cm).

As you can see the magnet was not so larger comparing with the decay volume.
Non-uniformity is serious

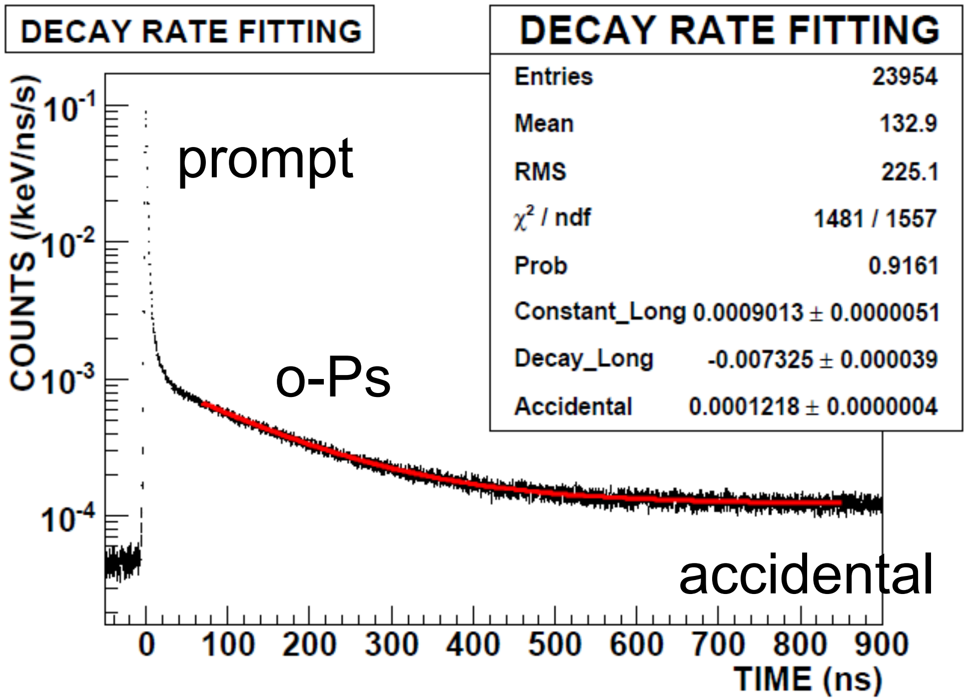
Uncertainty of the magnetic field makes the systematic error on the HFS directly. (enhanced by factor 2 when you interpret Δ_{HFS}).



Even now, it is difficult to control magnetic field with an accuracy of O(1ppm) for O(10cm) space

[2] non-thermalized Ps / annihilation background (1)

(1) e^+ emitted from ^{22}Na β source collides with e^- in the gas and makes o-Ps (5-10%). The orther e^+ just annihilates into 2γ or makes p-Ps decaying into 2γ immediately.
(They are in prompt peak less than 1 nsec.)
Only o-Ps events is target, but all events were used in the old experiments.
These were the serious background and S/N ratio was worse of ~ 0.05.

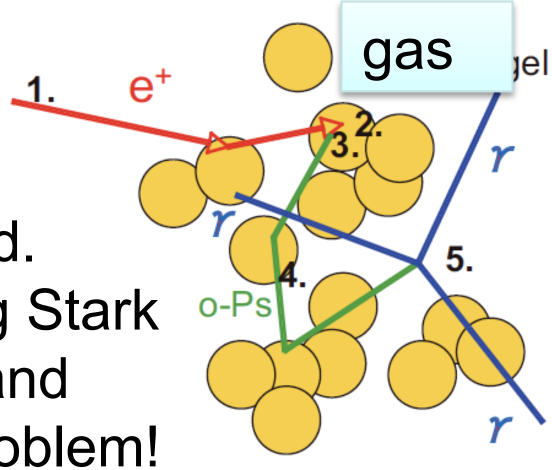


Time spectrum between e+ emission and γ detection.
Prompt peak: annihilation & p-Ps
o-Ps decay region

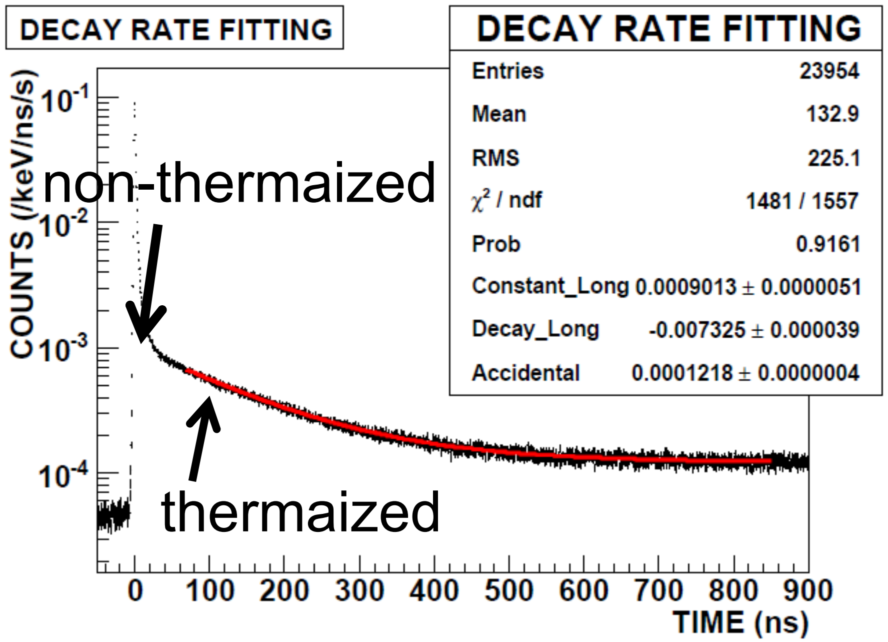
Now, we tag timing information and only the events (t>10nsec) is used.

[2] non-thermalized Ps / annihilation background (2)

Produced o-Ps also collides with gas molecular.
When o-Ps collides with the molecular, Ps feels the electric filed produced with molecular.
Then the energy-level shifts due to Strak effect (10ppm order). This Strak effect should be corrected.
The extrapolation method was used. (HFS including Stark effect were measured changing the density of gas, and extrapolate to zero density.) But There is serious problem!

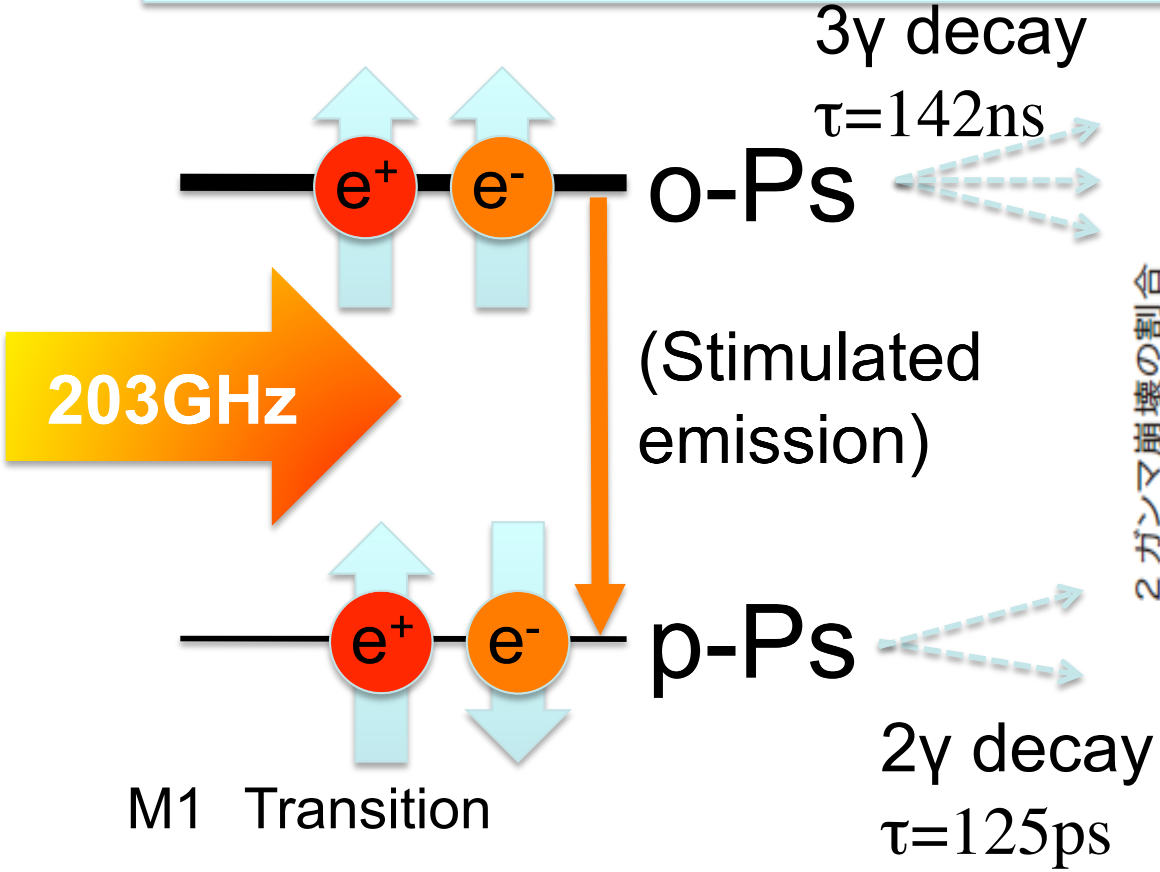


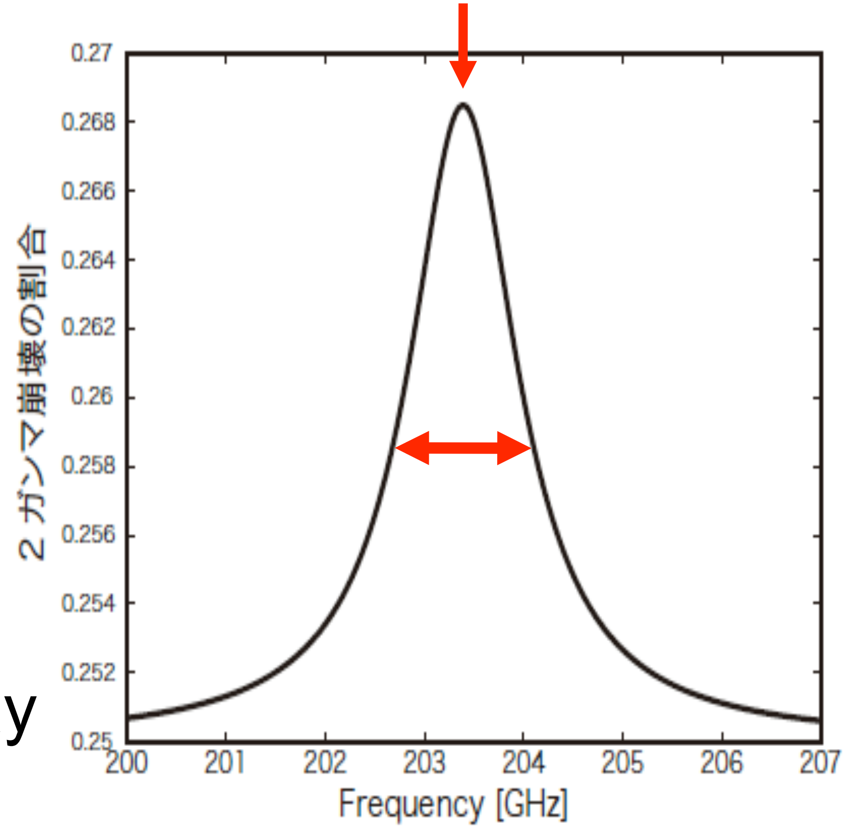
Effect is proportional to the density only when the velocitv of Ps is constant.
But Just after the formation, Ps has large velocity (E_{kin}~eV >> 1/30eV)
Ps becomes thermalized after O(10nsec) with the elastic collision with gas.
The non-thermalized Ps has larger the Stark effect.



Thermalized Ps events (t>O(10nsec)) should be used. (Time information is necessary)

Direct measurement of HFS (Simple!!)





(1) Apply “203GHz” sub-THz light on the “well thermalized o-Ps”,
then making the stimulated emission (M1 transition) of o-Ps to p-Ps:

(2) p-Ps decays into 2γ immediately, 2γ decay rate increases as a function of input frequency. → We obtain Brit Wigner resonance.

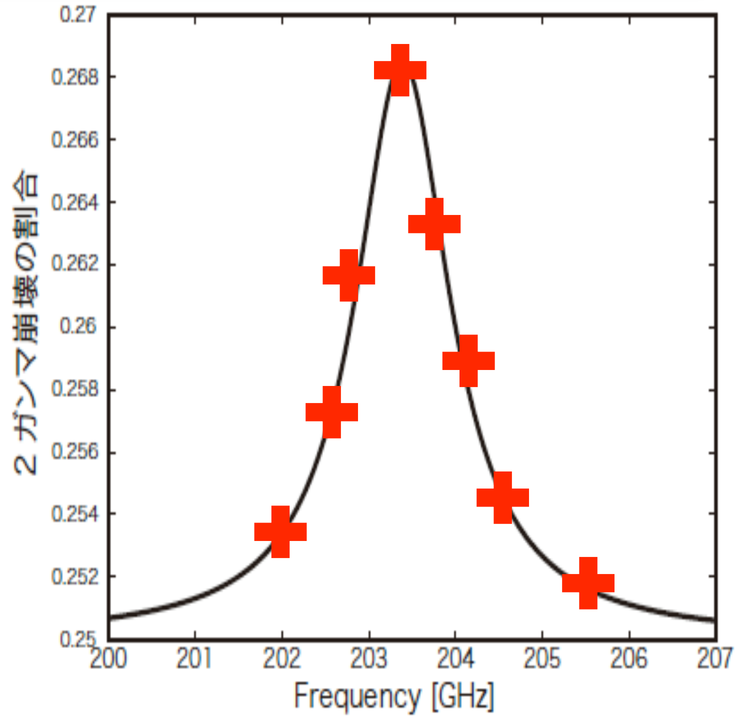
Center value HFS / width is corresponding to p-Ps decay rate.

(decay rate of p-Ps has not yet measured precisely. We have **double** chance)

But experimental technique is challenging !!!!

(1) This transition ($\Delta S=1$) is suppressed:
$f=3\times10^{-9}$ / s
→ We need high power > O(100) W
to observe the transition.

(2) To obtain BW resonance.
→We need “**tunable**” source
FWHM~1.2GHz
Several points are necessary
within range of 3GHz.



(3) CW operation is desirable. (Long time operation is also important.)

(4) Stable and accurate on frequency is need at O(1)ppm
Integrated power can be measured with an accuracy of (O(0.1)%).

(5) (Sub) THz powerful source is still under developing
and these feature is challenging but very useful for the fundamental physics!

GYROTRON is very powerful & promising source for (sub) THz

(Gyrotron FU CW V dedicated for HFS)

Power = 609W (measured)
Frequency 203.08 GHz
dedicated for HFS
Monochromatic < 10kHz

Now under developing :

(1) Tunable mechanism using Backward-Wave Oscillator.

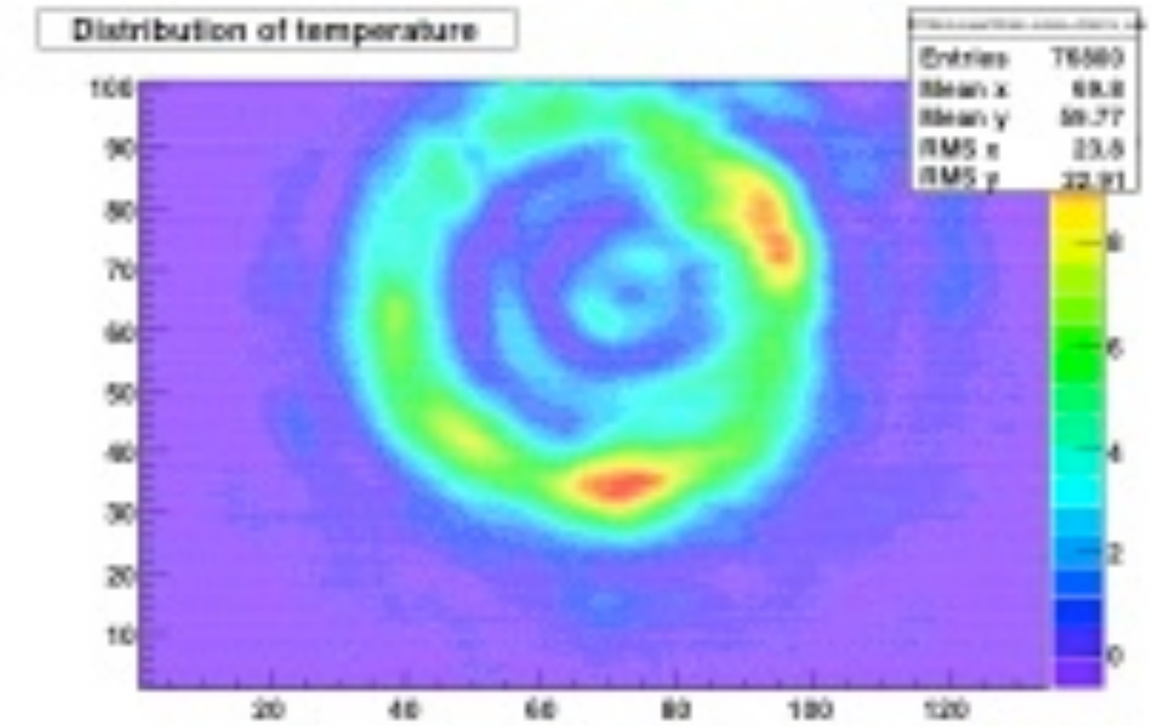
(See. talks by Chang-san and Ogawa-san)

(2) Feedback power information to initial electron gun for power stability

(3) Temp. vacuum quality control for frequency stability for long time

Output of this Gyrotorn is TE03 mode

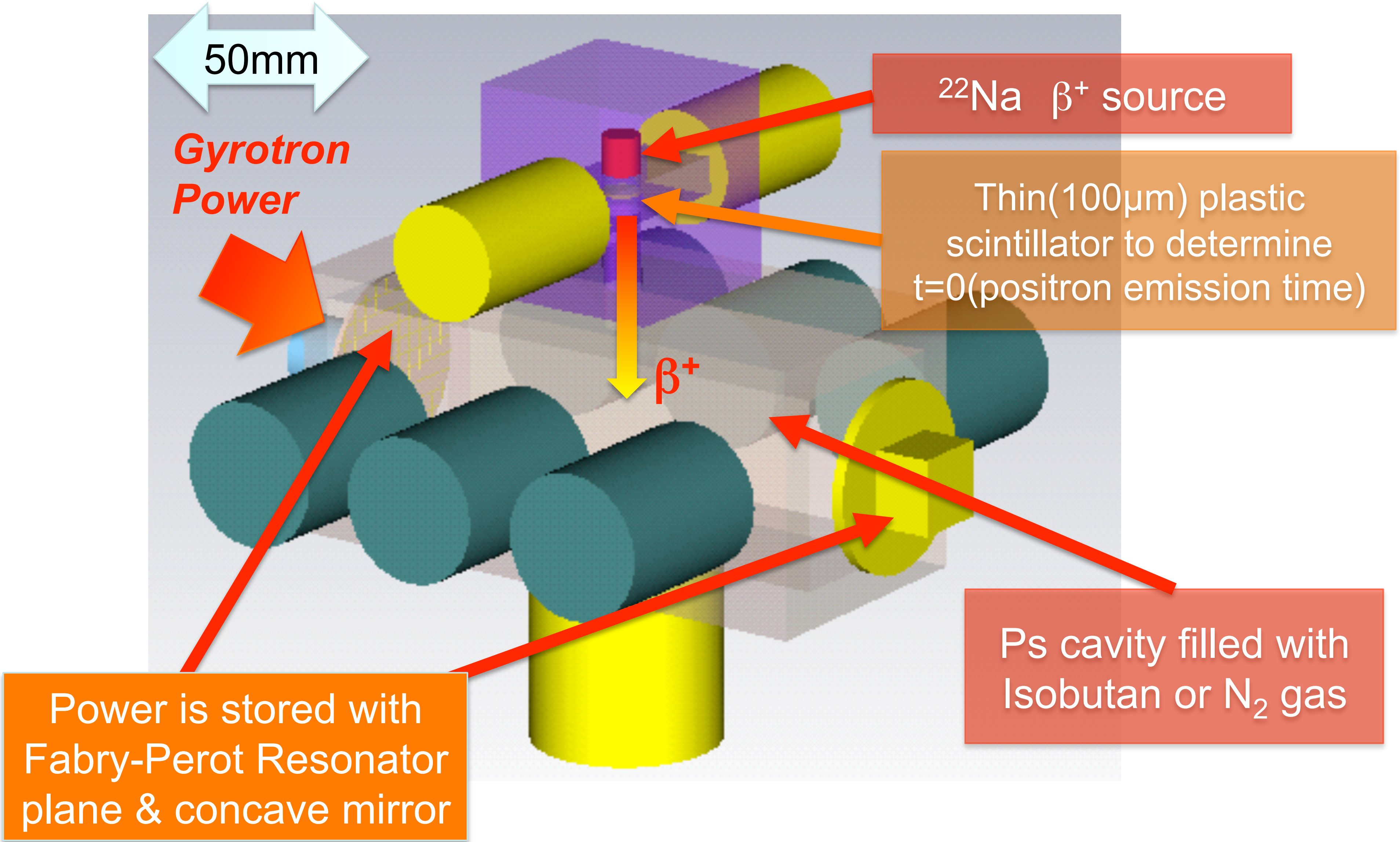
This shows power distribution measured with
the infrared camera: (160mm away from waveguide)



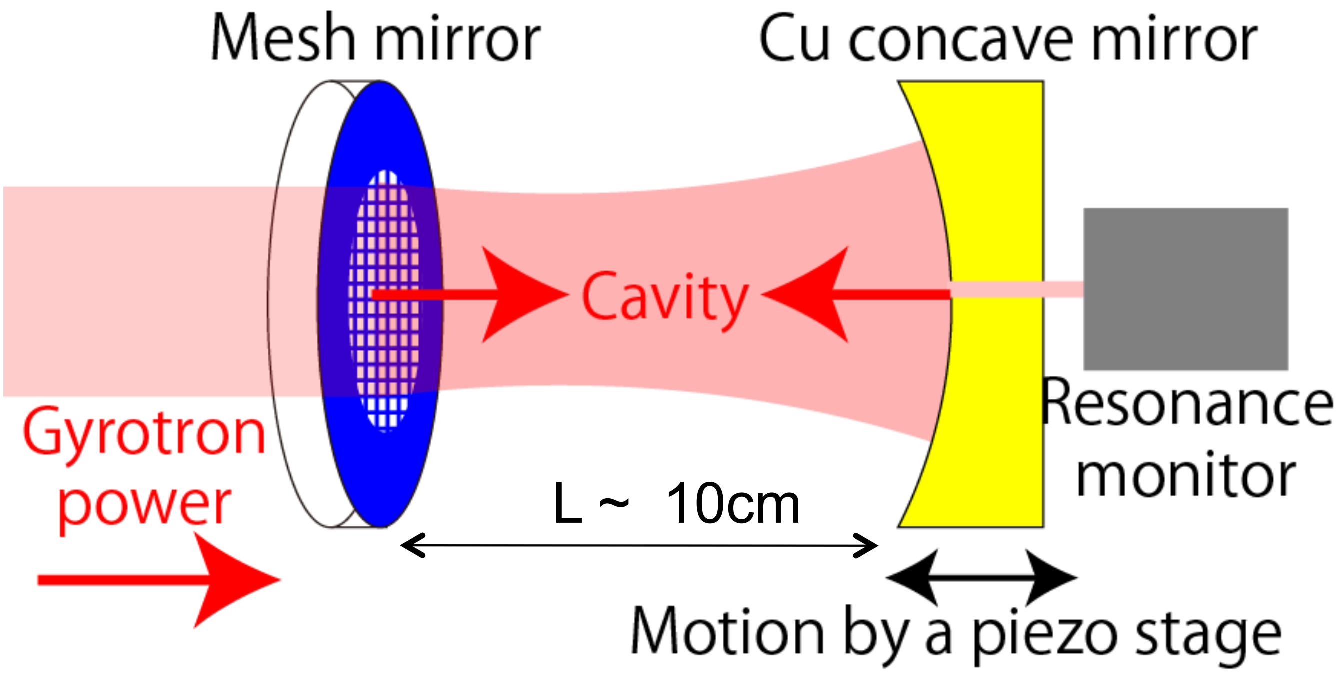
TE03 mode is converted to "Gaussian mode".   in which the energy will be concentrated into center:
transfer power loss can be suppressed and couple with the PS cavity effectively.

Detail of the measured optics of the Gyrotron,
and design of the Gaussian-Converter
are presented by Dr. T.Suehara
(Tomorrow afternoon)

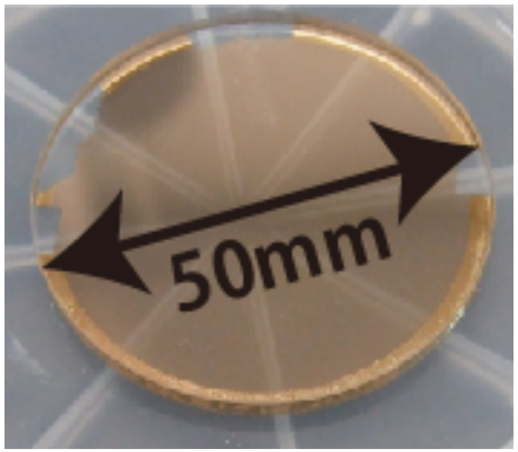
Experimental Setup

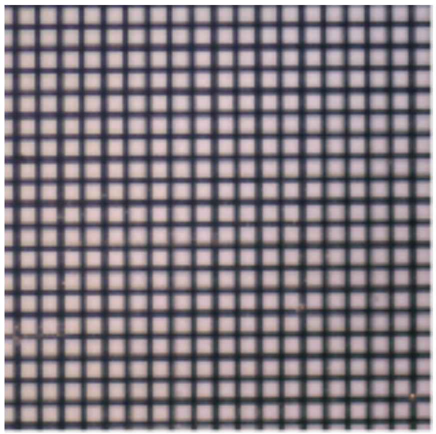


Fabry-Perot Cavity



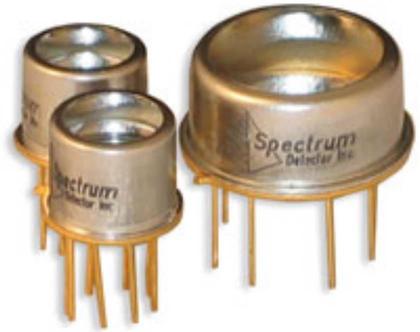
Cu concave Mirror
R=300mm
L=50~150 mm
Mirror is controlled
with piezo stage:





Mesh plane mirror:
Thin gold is formed
on the quartz:
width and interval
and 20 and 50μm,
(or about 200μm both)

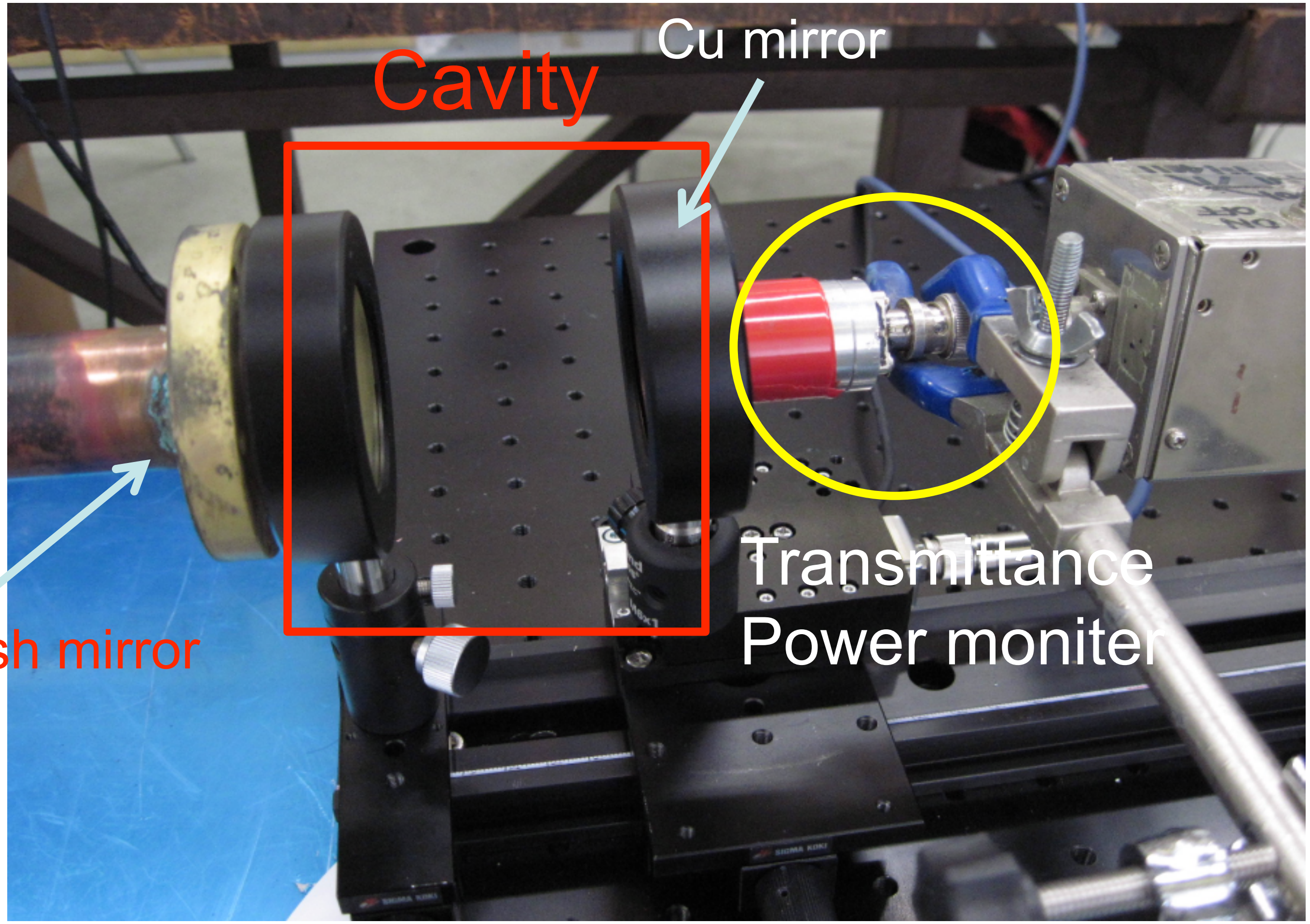
Power monitors



Small hole (Φ=0.6) and Pyro-thermal detector is installed behind the cu-mirror   to measure **Transmittance power**

Reflectance power monitor is also installed using half-mirror

203GHz power



Finesse

$$\mathcal{F} = \frac{\delta\nu}{\Gamma} \sim \frac{2\pi}{1-\rho}$$

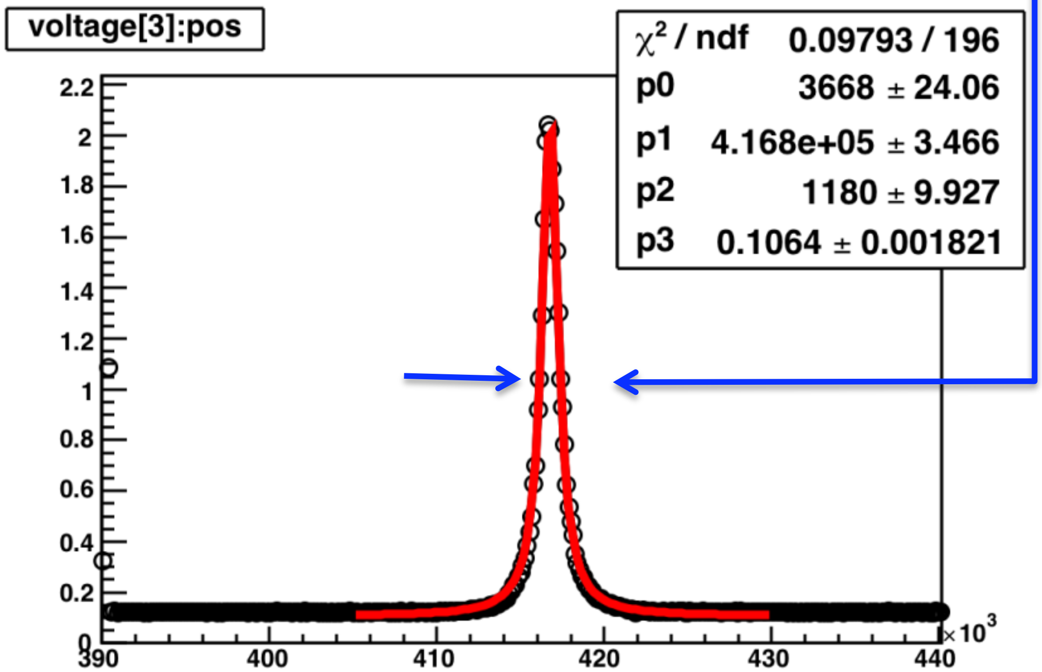
ρ: Reflectance

F～650 is obtained.
It means about 100 times round trip of photon between two mirror.
ρ~1% (loss) is achieved.

Cu mirror loss ~0.2%
Mesh mirror loss ~0.4%
Diffractive loss ~ 0.??%
(Not yet finalized)

Can be determined by resonance curve (resonance width and position)

Measured resonance by



Coupling

Power in Cavity is proportional to Coupling

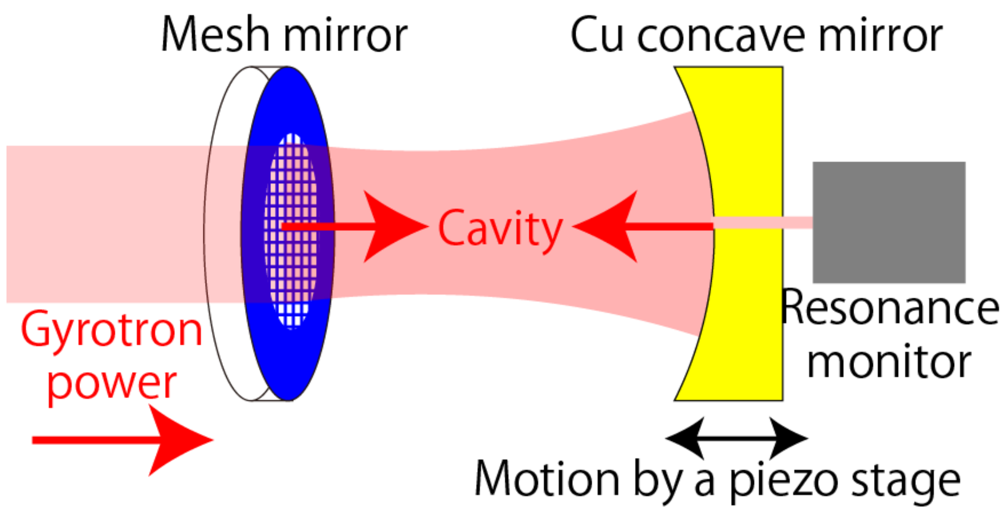
$$P_{\rm acc} = C \left(\frac{F}{\pi}\right)^2 P_{\rm in}$$

$$C = T_{\rm b} T_{\rm mesh} C_{\rm mode}$$

T_b: beam transmission loss
~50-70% (loss in mesh is large)

Tmesh: mesh Transmittance
T_{mesh} ~ 1-R ~ 1/F

C_{mode}: Cavity mode



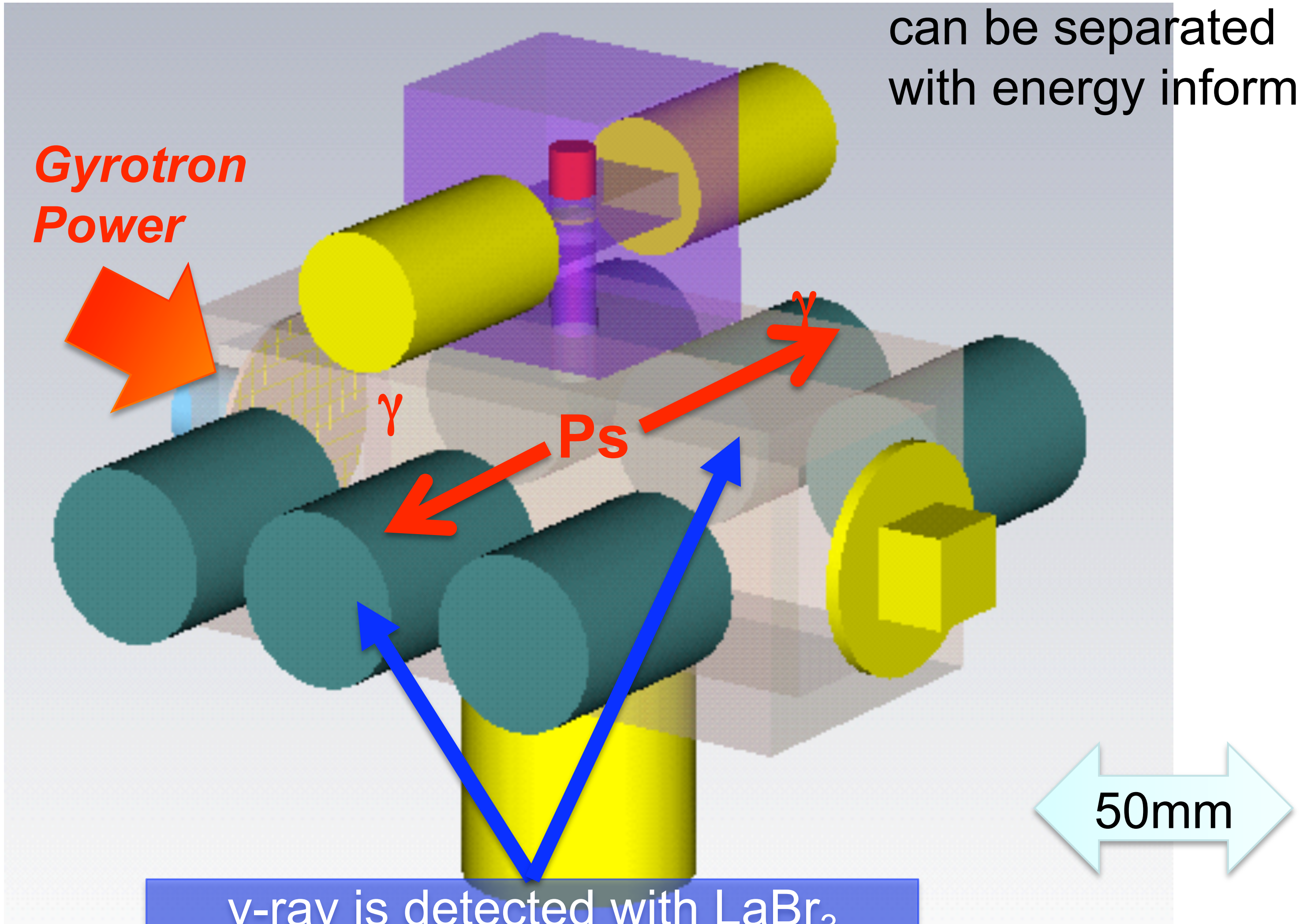
Mode which match to the Cavity resonance mode
passes through and stored
in the Cavity.
Match beam waist, size ,,,,,

Mode matching between transmission and cavity is crucial:
Detail is shown by Dr. T.Suehara in tomorrow afternoon.

Photon detector & timing information

o-Ps decays into 3γ (continuous distribution)
Transited Ps(p-Ps) decays into 2γ (monochromatic 511keV)

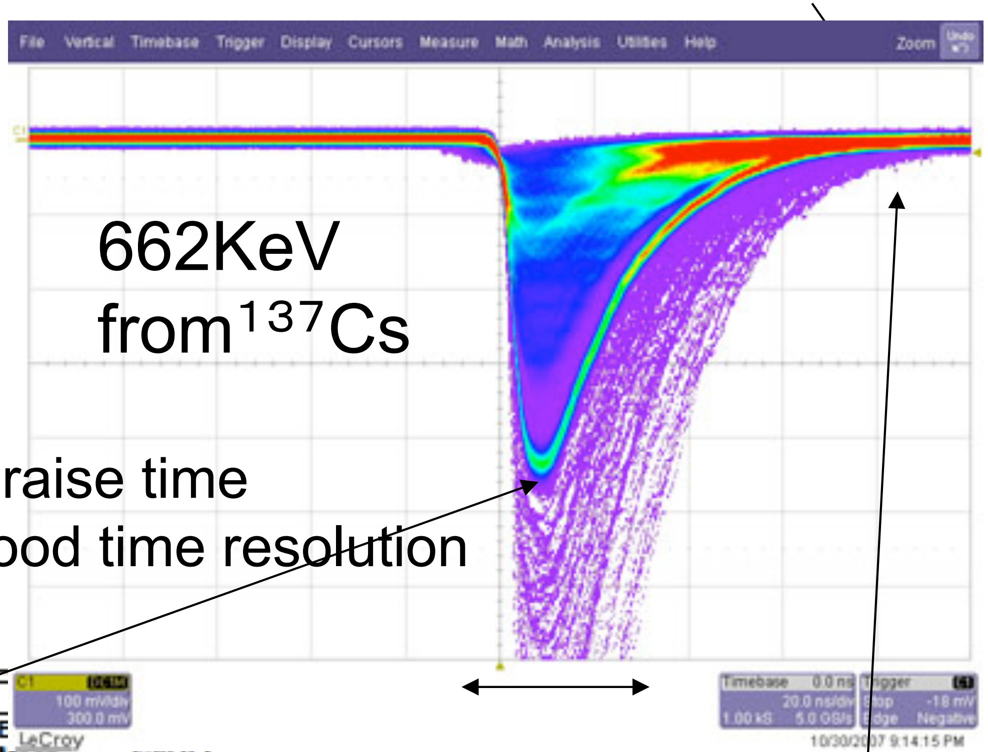
can be separated
with energy information



γ-ray is detected with $LaBr_3$ scintillator.

$LaBr_3$ Scintillator

This shows observed signal

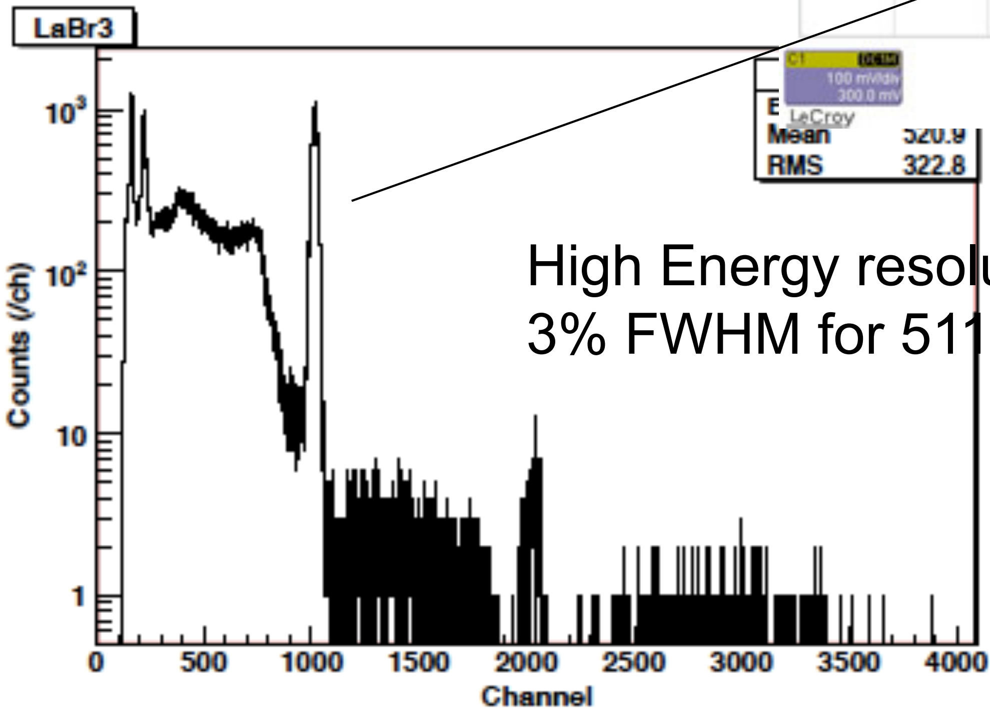


662KeV from ^{137}Cs

Fast raise time
-> Good time resolution

40nsec Fast

No slow component
Pileup effect is small



High Energy resolution
3% FWHM for 511keV γ

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

Summary & Prospect

(1) Ps is the lightest atom
There is 3.9σ discrepancy in HFS between the QED prediction and the measured values.

(2) There are two possible systematic errors in all old experiments.
magnetic field and non-thermalization

(3) We propose new method free form these errors:
(No magnet , direct transition)

(4) Gyrotron is suitable for the direct transition.
Under-developing for tunable, stability on power & frequency.
Gaussian convert from TE03 will be used,

(5) Fabry-Perot cavity: Finesse OK: Still under-developing on coupling

(6) In 2010 observation (first observation) of the direct transition in SubTHz region.
In 2012 precise measurement HFS and p-Ps lifetime directly.

The other applications

(1) ν EDM mass~ sub THz region
(2) Axion-photon conversion
(3) Axion quark transition
(4) Dark energy ??
(5) ………………..

Still investigating

High Power & Accurate (sub) THz source is also useful for the fundamental physics.

おまけ

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

Phy. Rep. 422(2005) 1.

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.

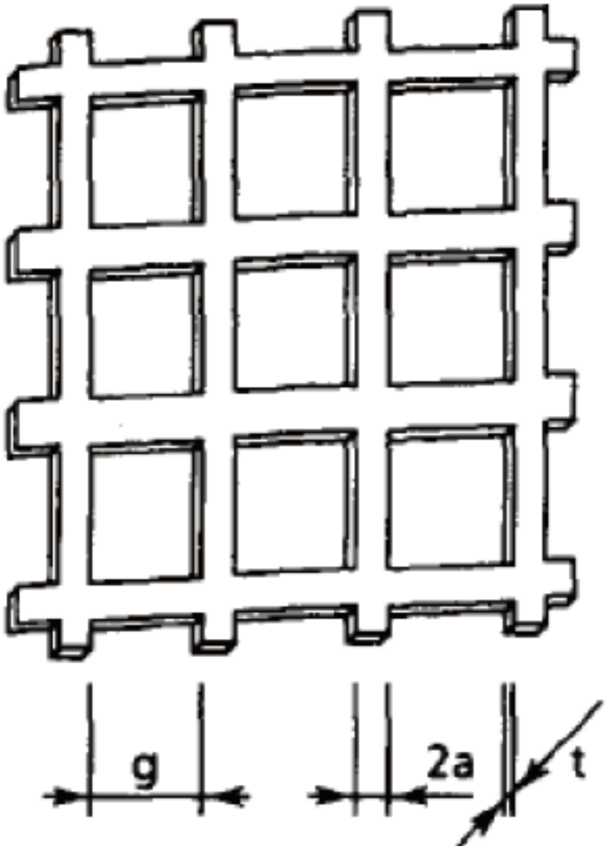
o(α2) 100ppm level correction are calculated at 2000

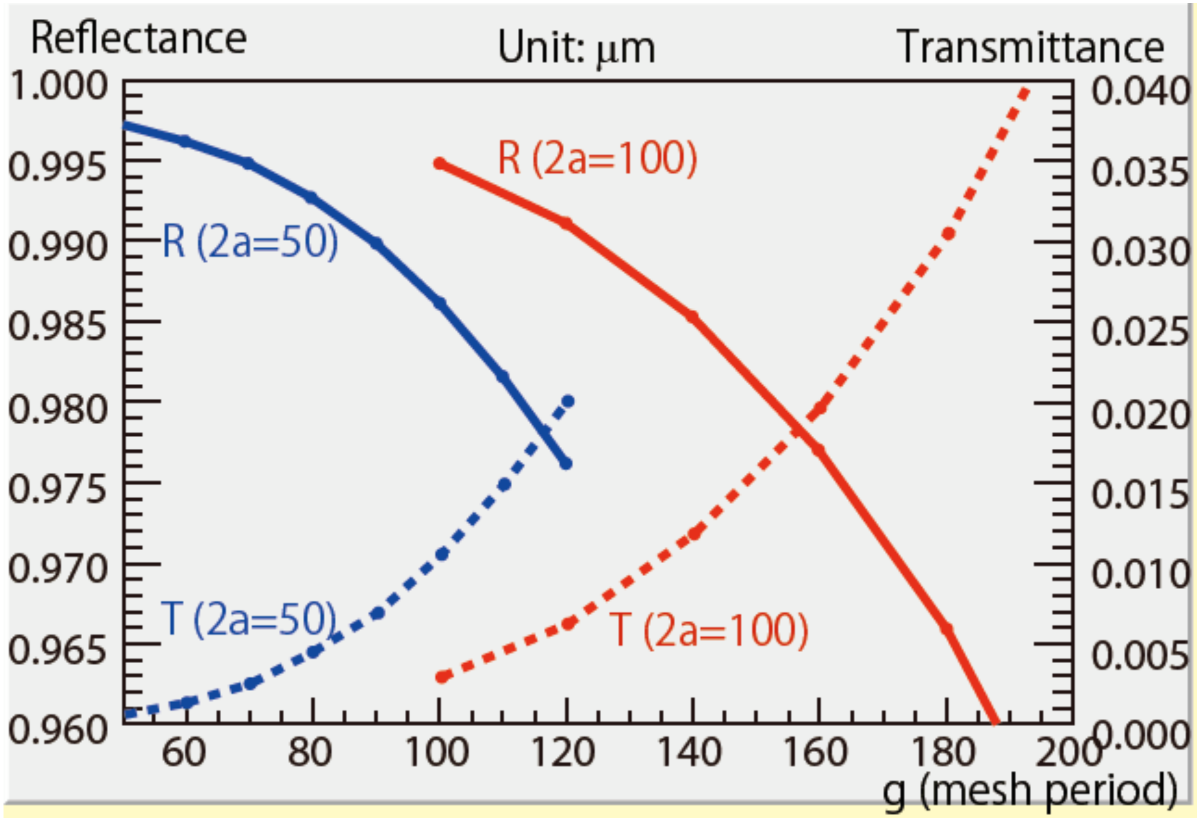
Table 13
Theory of the 1S hyperfine interval in positronium

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

o(α3), 6ppm level correction, are calculated at 2001

These detail studies are motivation of our research.

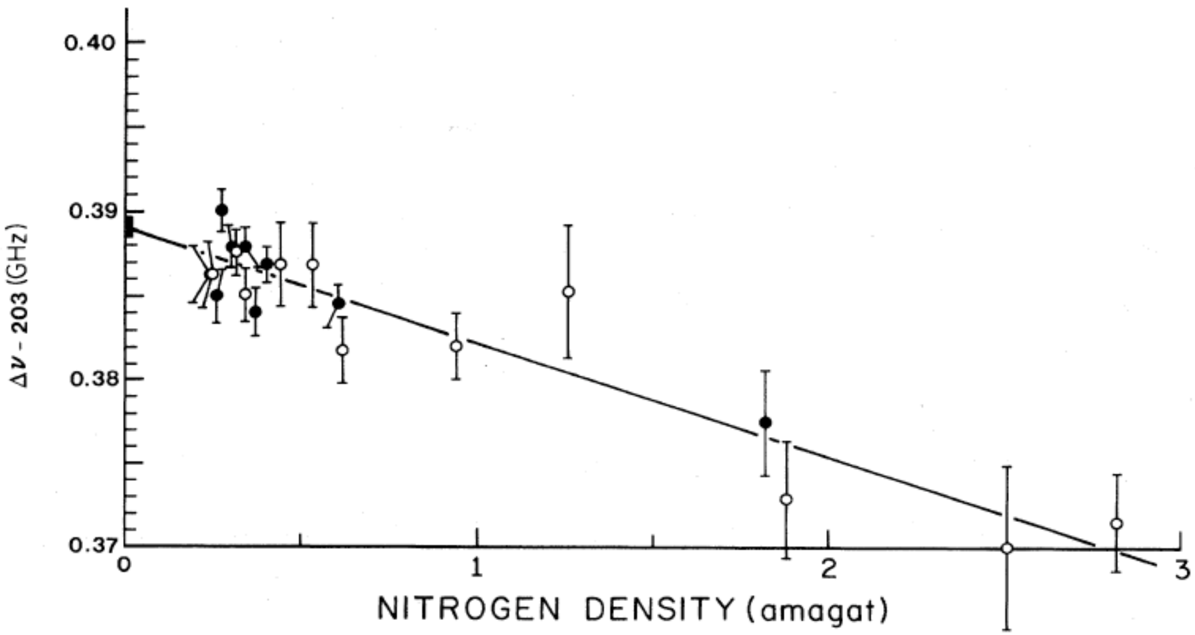




Large Gap -> Good Transmittance / but Low Reflectance

Material effect and non-thermalized o-Ps

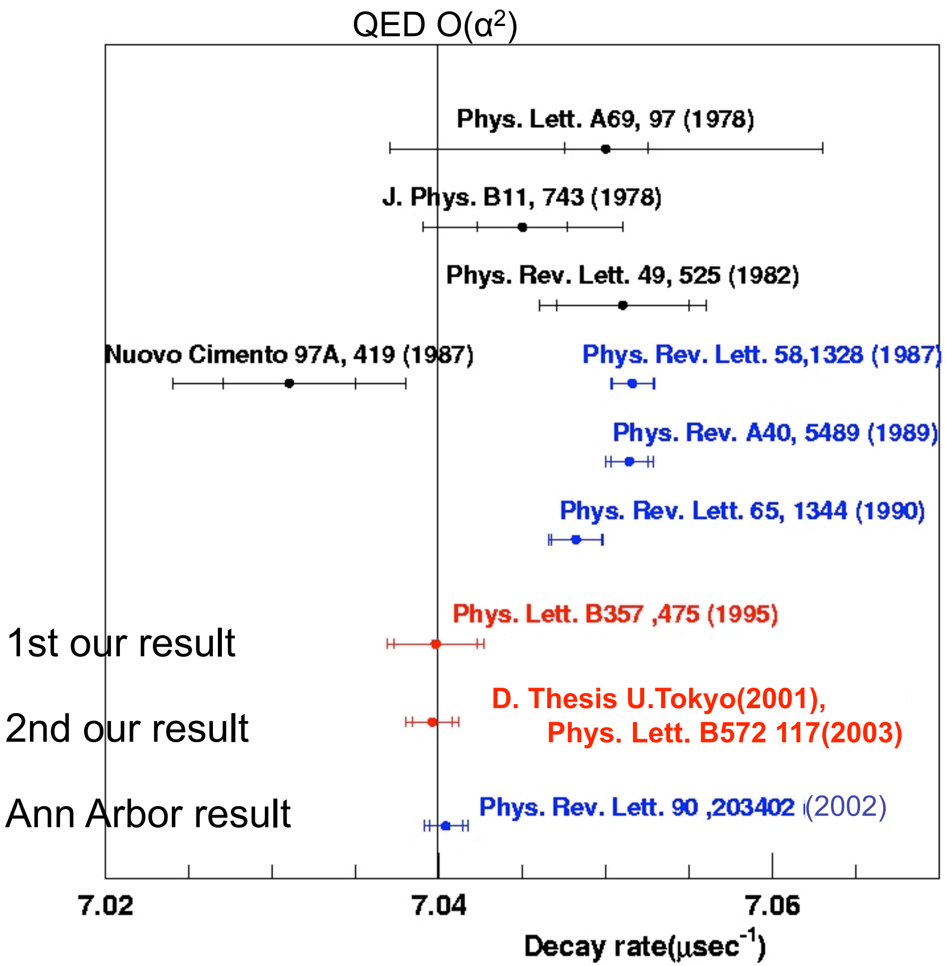
As the same as the measurements of o-Ps decay rate, material(gas) is used to make Ps, and the produced Ps collides these material. Close to the material, the Ps feels the electric filed produced with the material, and the energy-level shifts due to Strak effect(10ppm order). This material should be corrected,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

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.

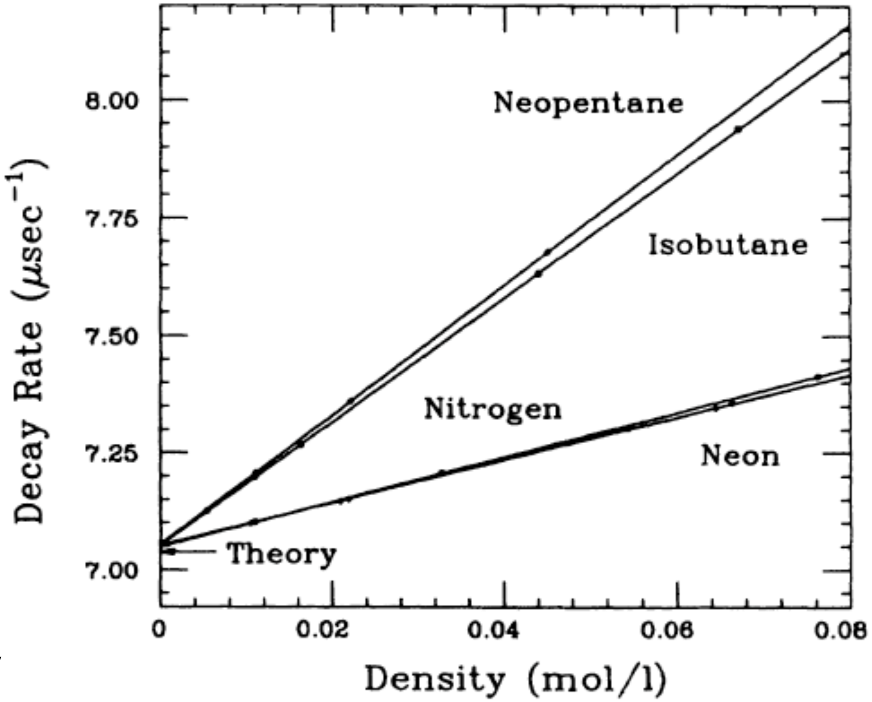
Pick-off annihilation (Material effect)

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 $\lambda_{3\gamma}$

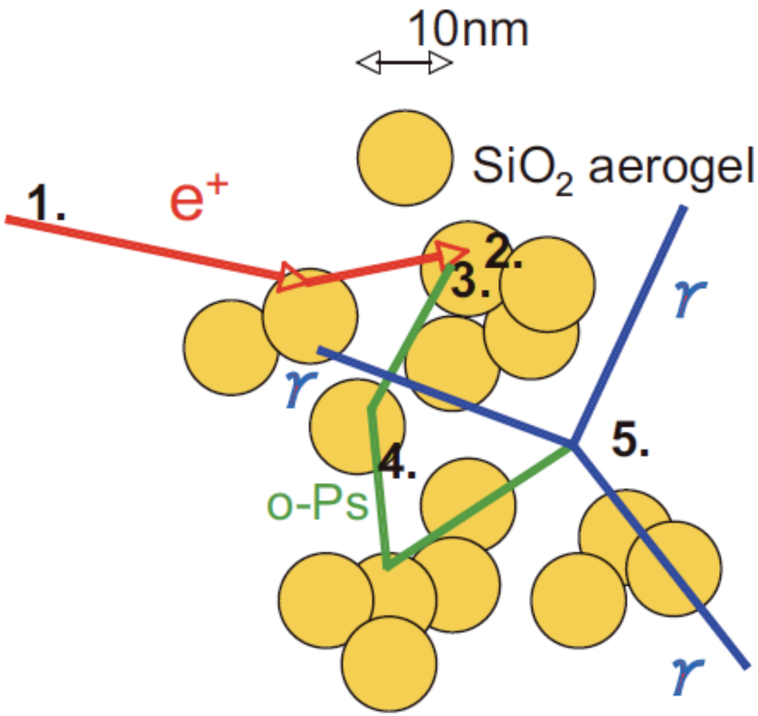


Phys. Rev.A40(1989) 5489

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

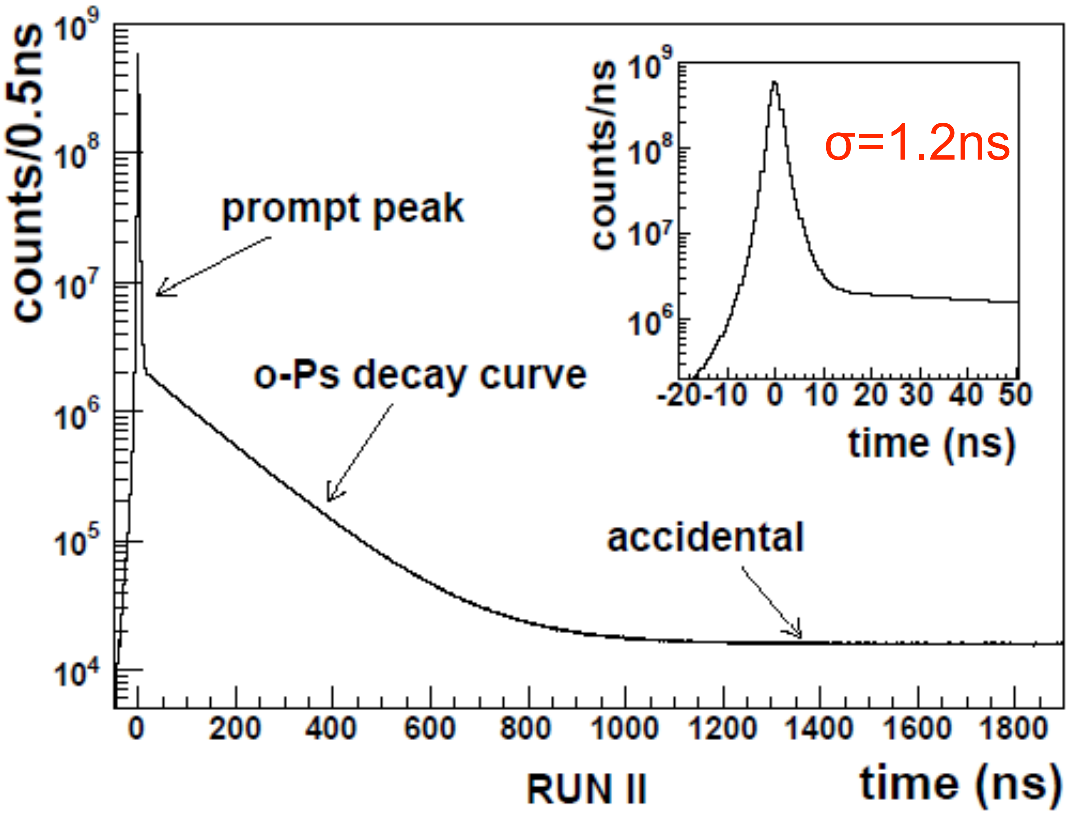
→ $\lambda_{pickoff}$ becomes higher.

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

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.

[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:

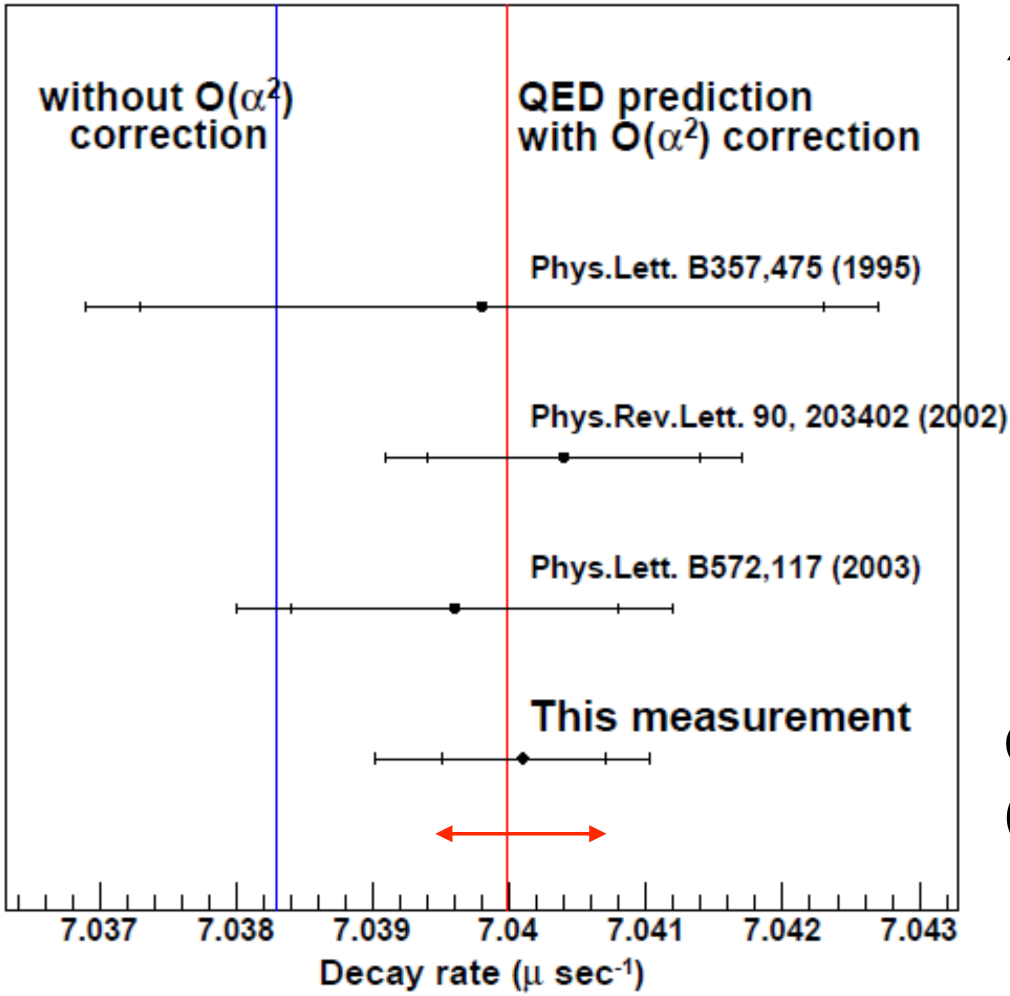
Measured pick-off ratio is used.

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

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

Decay rate can be obtained without extrapolation.

[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