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Hyperfine resonance of positronium using a static periodic magnetic field

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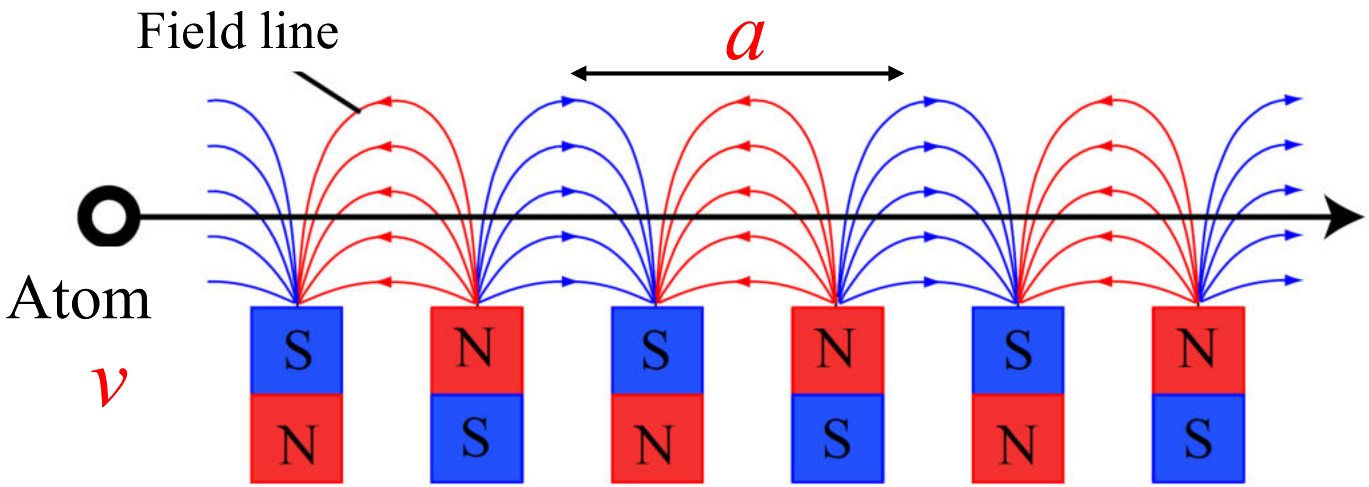
v2.1

Atomic resonance using a static magnetic field
Motion-induced resonance (MIR)



A. Haakeyama et al., Phys. Rev. Lett. **95**, 253003 (2005)

- Oscillation frequency $f = v/a$.

  a : period length

  f : atomic velocity

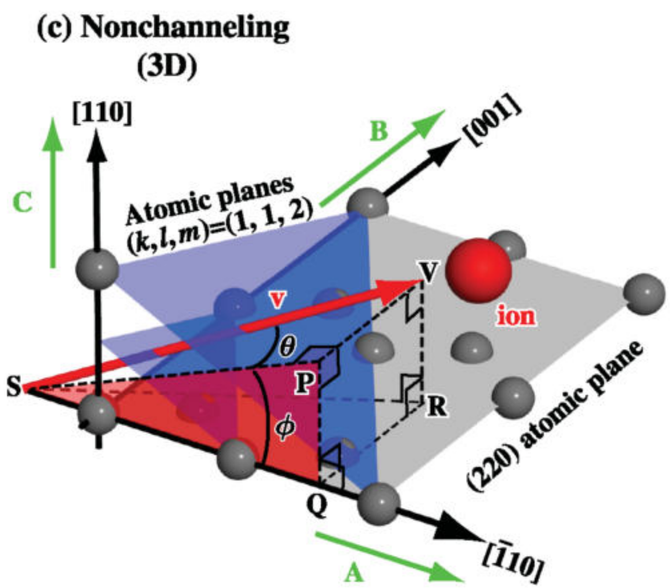
- **If f = atomic resonance frequency**

  → **Motion Induced Resonance (MIR)**

- MIR using a magnetic field was demonstrated only for ~1 MHz so far.

MIR using a crystalline field (electric field)

Crsytalline field



C. Kondo et al., PRL 97, 135503 (2006)

Okorokov effect (1965)

Resonant coherent excitation(RCE)(1978)

Electric field ： 100 GV/m
→comparable to a high-intensity ultrashort pulse laser

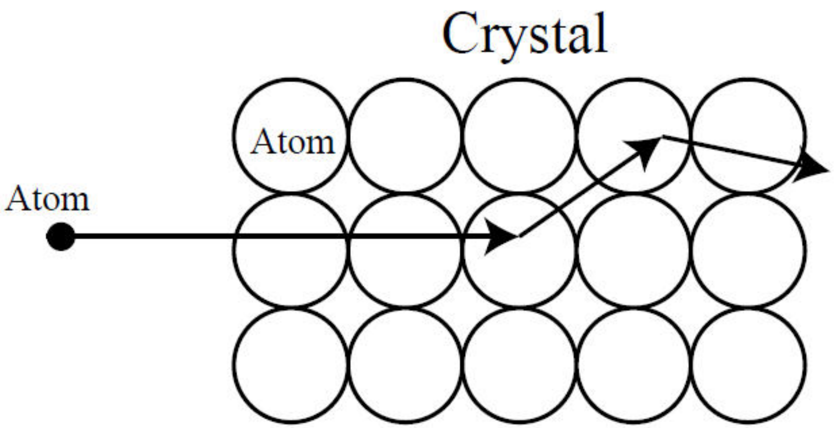
- Manipulation of energy levels of highly charged ions (Ar^{17+} 1s→2p) [1]
- Polarization control of highly charged ions [2]
- Precise spectroscopy of Li-like U^{89+} ions 2s-2p transition (X ray region) [3]
  QED test （0.1%）

Disadvantage

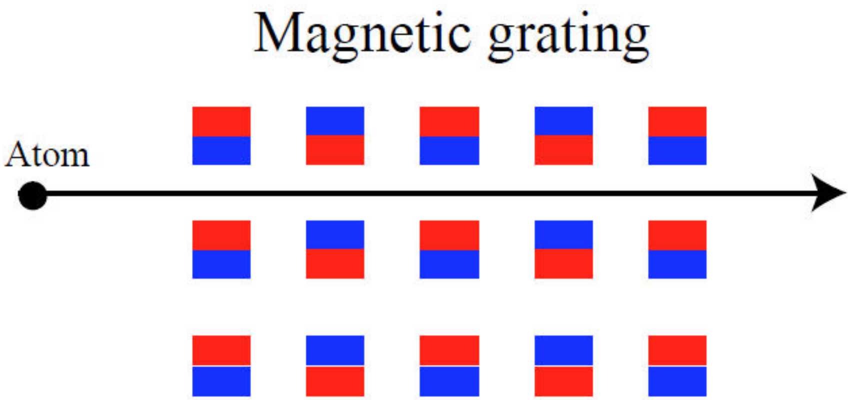
Scattering with atoms in a crystal
（not suitable for positron）

[1] T. Azuma et al., Phys. Rev. Lett. **83**, 528 (1999).
[2] Y. Nakano et al., Phys. Rev. Lett. 102, 085502 (2009).
[3] Y. Nakano et al., PRA **87**, 060501(R) (2013) .

Motivation



Periodic field felt by atom is disturbed by the scattering



Not disturbed (keep coherence)

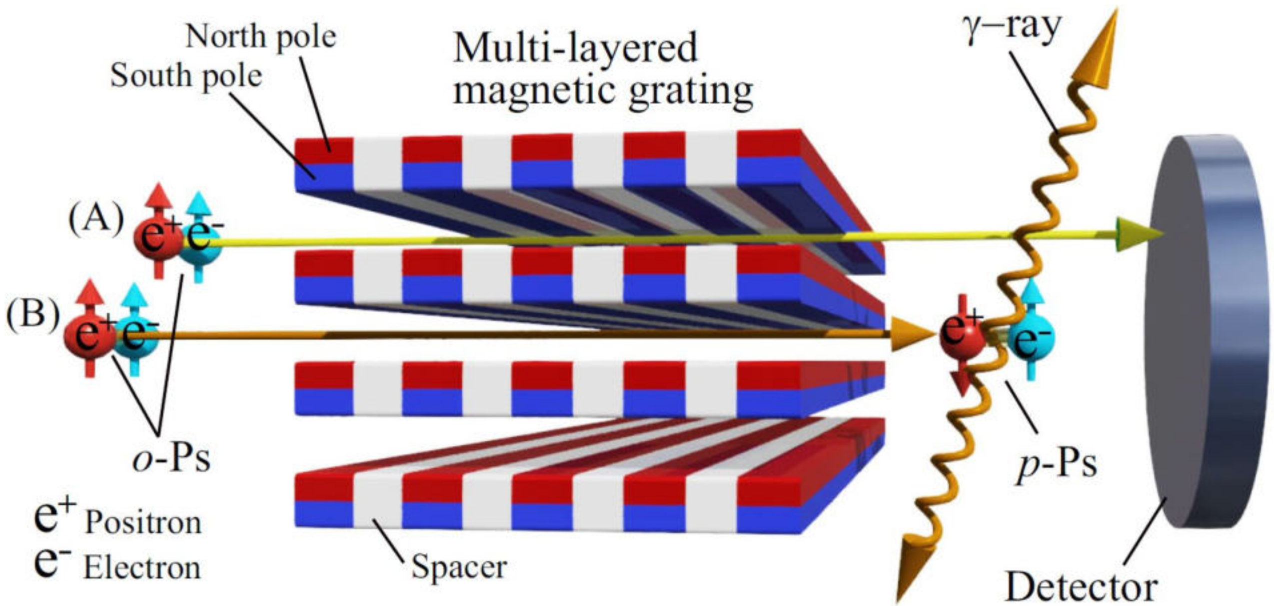
- **Motion Induced Resonance (MIR) of Ps hyperfine structure (203 GHz) is observed by using energy-tunable Ps beams.**
- First observation of MIR in the system of antimatter and exotic atoms.
- First observation of MIR in the sub-THz region

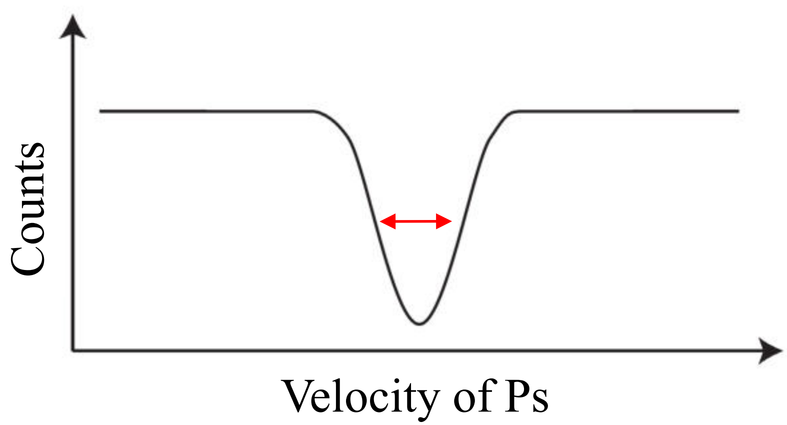
(Ps hyperfine transition frequency 203 GHz was observed indirectly [1], or directly using a strong milli-wave source [2].)

[1] A. Ishida et al., Phys. Lett. B **734** (2014) 338.
[2] A. Miyazaki et al., Prog. Theor. Exp. Phys., (2015) 011C01.

Concept of the experiment

MIR of Ps hyperfine structure (203 GHz)

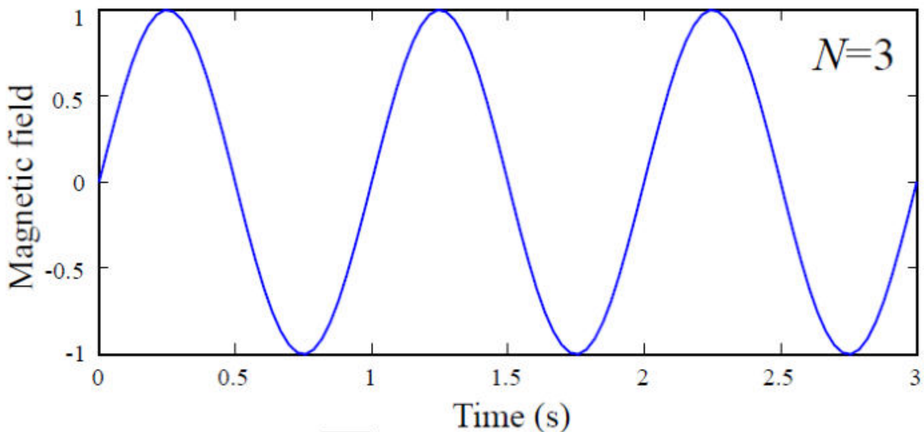


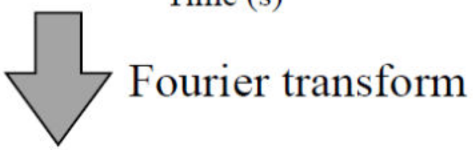


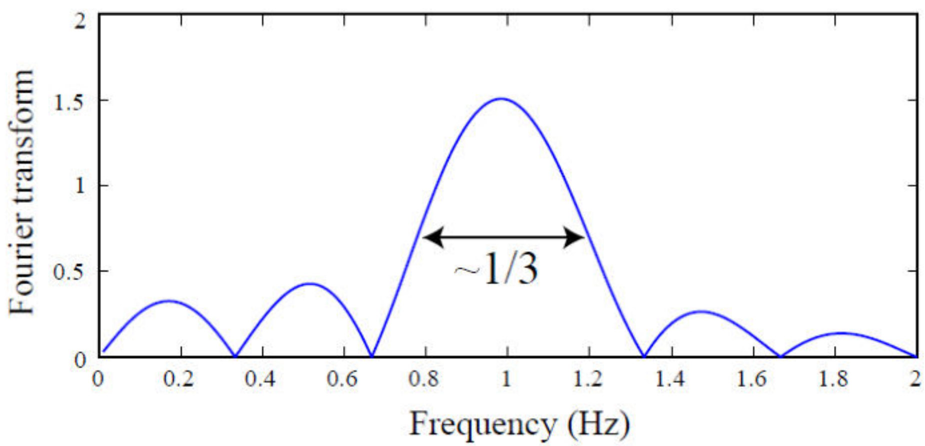
Rrequirement for a multi-layered magnetic grating

- Ps velocity v=1.8 × 10^7 m/s @ 1.8 keV.
- Period length $a = v$ / 203 GHz ～ 90 μm.
- 10 period pass length = 0.9 mm / 1.8 × 10^7 ～ 50 ps.
- More than **0.1 T** is needed for 50 ps transition (considering Rabi frequency).

Resonance width of MIR







Fourier transform for N cycles

$$|F(w)| \propto \left| \int_0^{NT} \sin(w_0 t) e^{iwt} dt \right|$$

$$= \left| \frac{2w_0}{w^2 - w_0^2} \sin\left(\frac{wNT}{2}\right) \right|$$

$\omega = \omega_0 + \delta\omega$

Expansion with respect to $\delta\omega$

$$|F(\delta w)| \sim \frac{\pi N}{w_0} \left(1 - \frac{(\delta w NT)^2}{24}\right)$$

Condition for FWHM

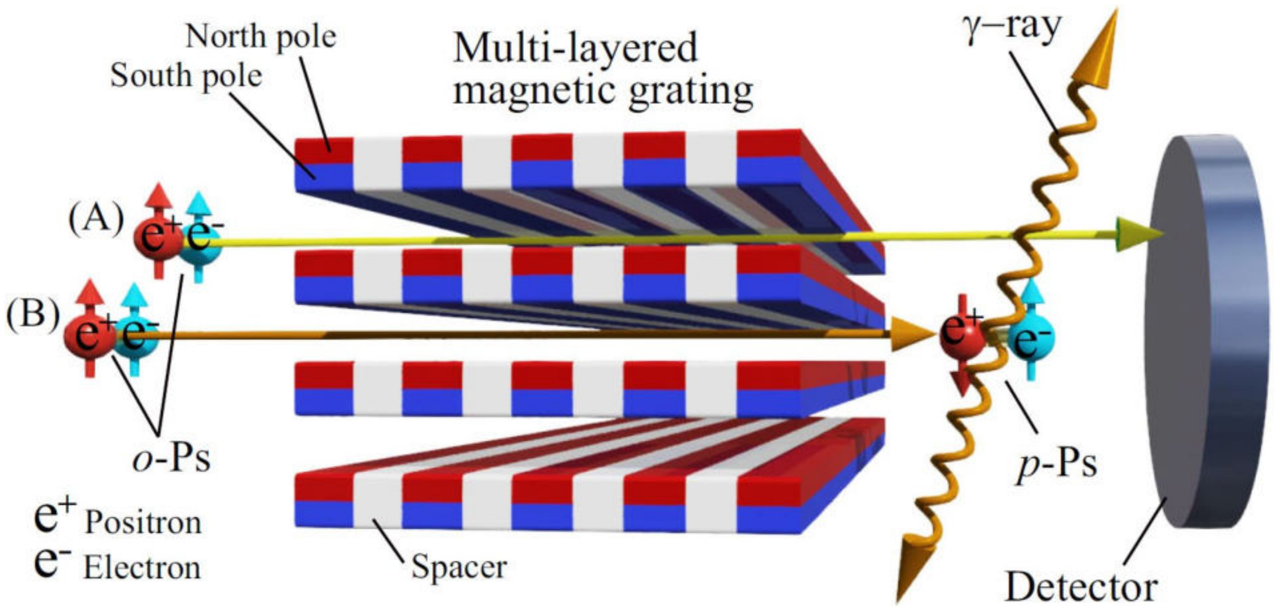
$$|F(0)|/2 = |F(\delta w)|, \ \delta w \sim \frac{\sqrt{12} f_0}{N}$$

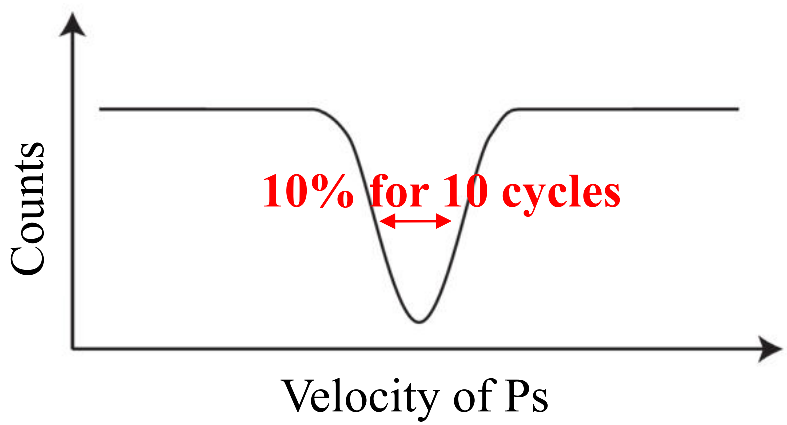
FWHM= $2\delta w$

Resonance width = FWHM / ω_0 ~**1/*N***

Concept of the experiment

MIR of Ps hyperfine structure (203 GHz)





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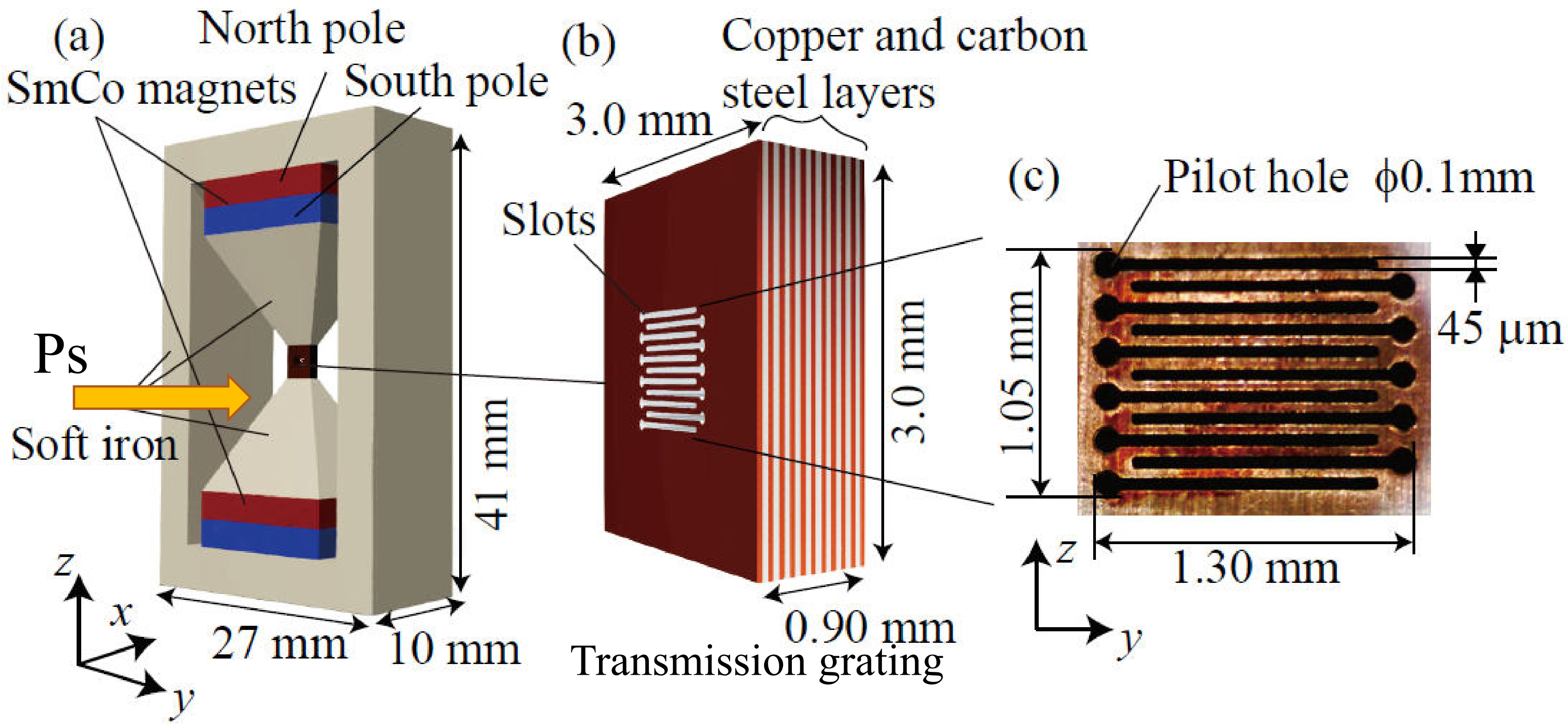
Multi-layered magnetic grating

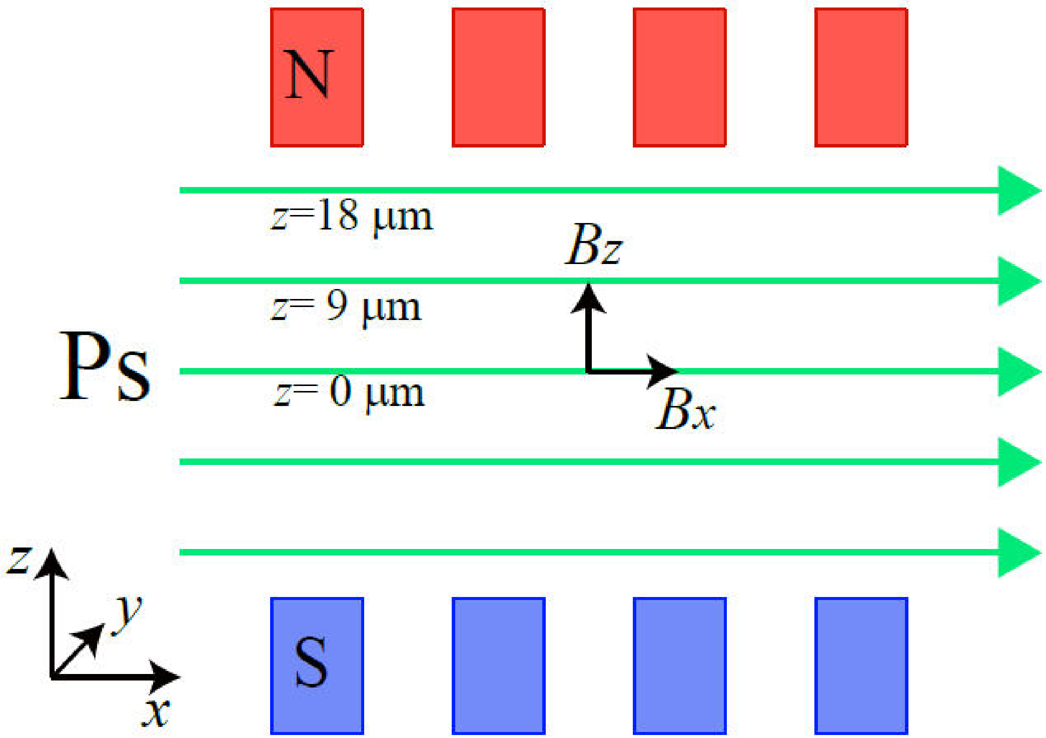
Period length 90 µm (Carbon steel 50 µm^t , Copper 40 µm^t)
10 layers

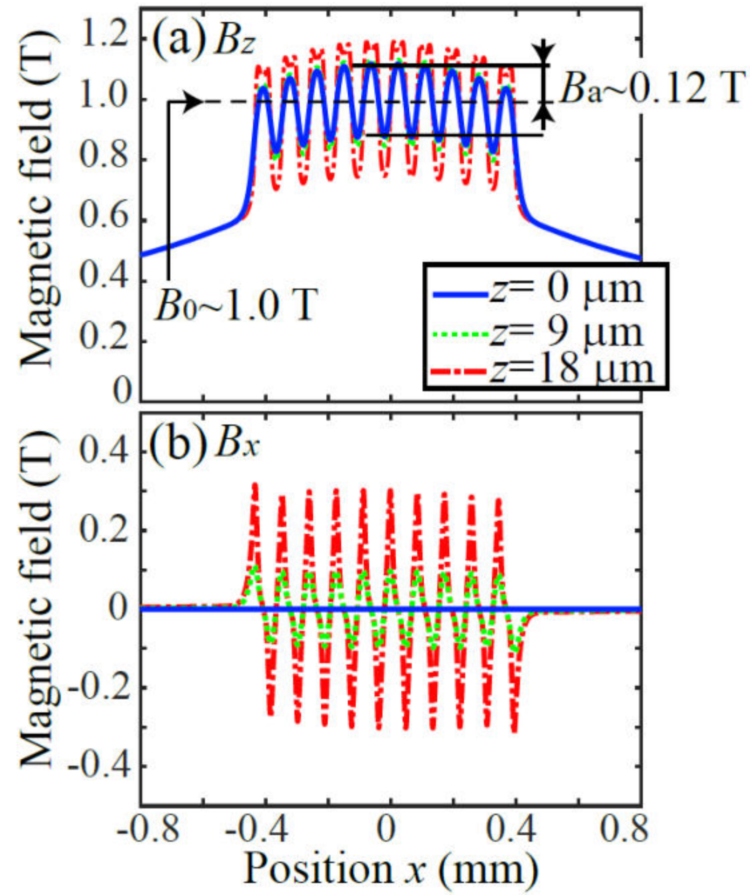


- Magnetization by SmCo magnets.
- Assembly by diffusion bonding vacuum hot press.
- Slots made by electrical discharge machining.

Y. Nagata et al., Phys. Rev. Lett. **124**, 173202 (2020)

Static periodic magnetic field calculated





Amplitude 0.12 T is enough to induce Ps hyperfine resonance.

- Amplitude 0.12 T. Power $cB^2/2\mu_0 \sim$ 100 MW/cm^2.
  (Fabry perot cavity by a strong milliwave source 10 kW/cm^2, reported in [A. Miyazaki, Ph.D. Thesis, The University of Tokyo, 2013])
- Bias field ~1 T

Y. Nagata et al., Phys. Rev. Lett. **124**, 173202 (2020)

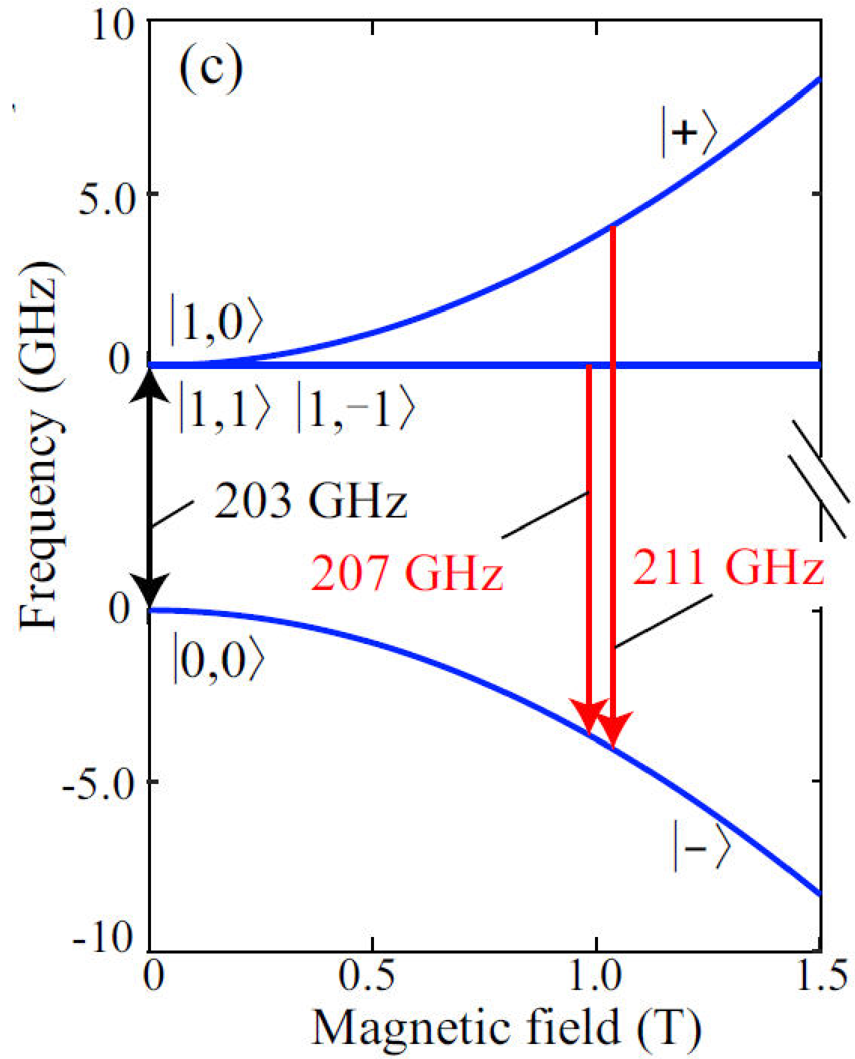
Ps hyperfine transition frequency expected

Hyperfine transition of Ps (1^3S_1-1^1S_0) in the magnetic field of 1 T

$|1,0\rangle \rightarrow |0,0\rangle$: 211 GHz @1T

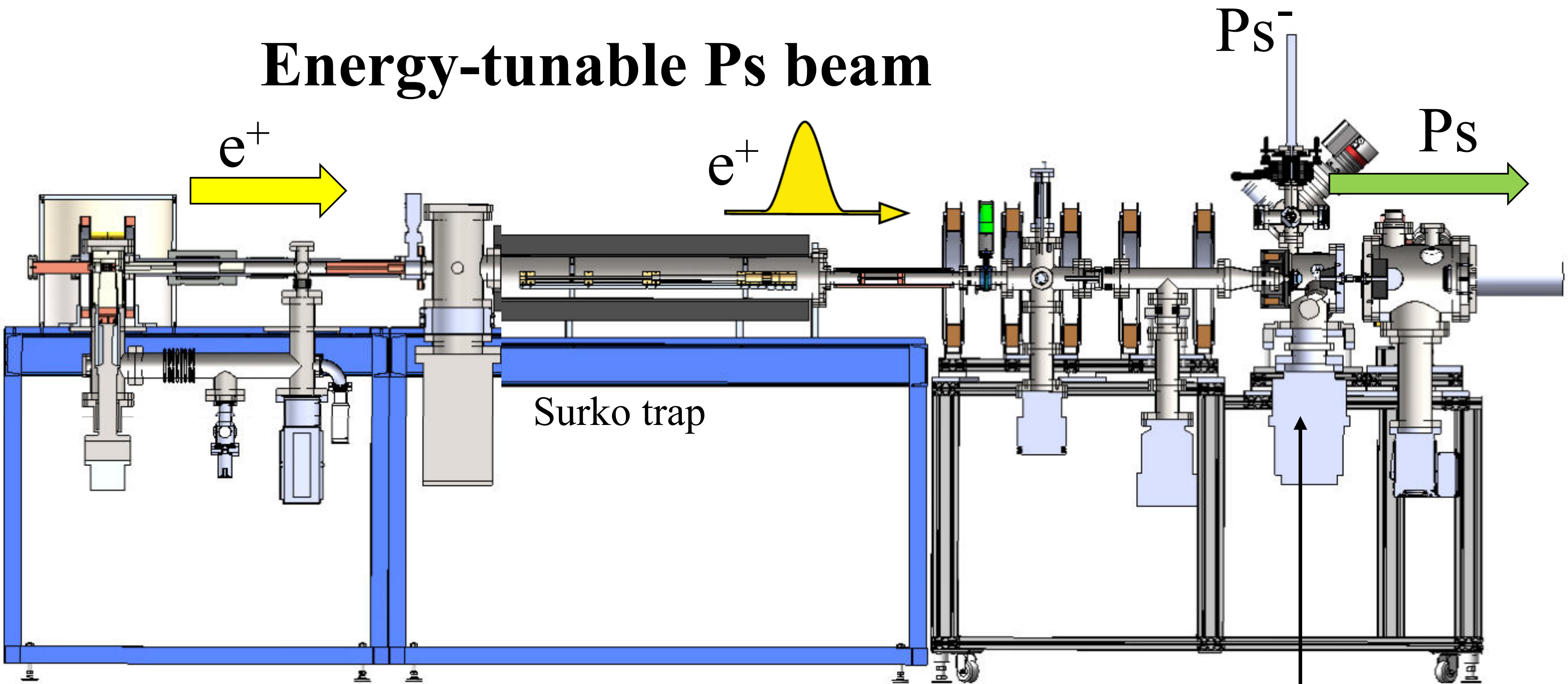
$|1,1\rangle \rightarrow |0,0\rangle$: 207 GHz @1T

$|1,-1\rangle \rightarrow |0,0\rangle$: 207 GHz @1T



The resonance frequency is 207 GHz and 211 GHz

Energy-tunable Ps beam



DC e+ source [1]

^{22}Na (20 mCi)
soild Ne moderator
efficiency：1%
Intensity：4×10^{6}/s
Energy : several eV

Trap based pulsed e+ source [2]

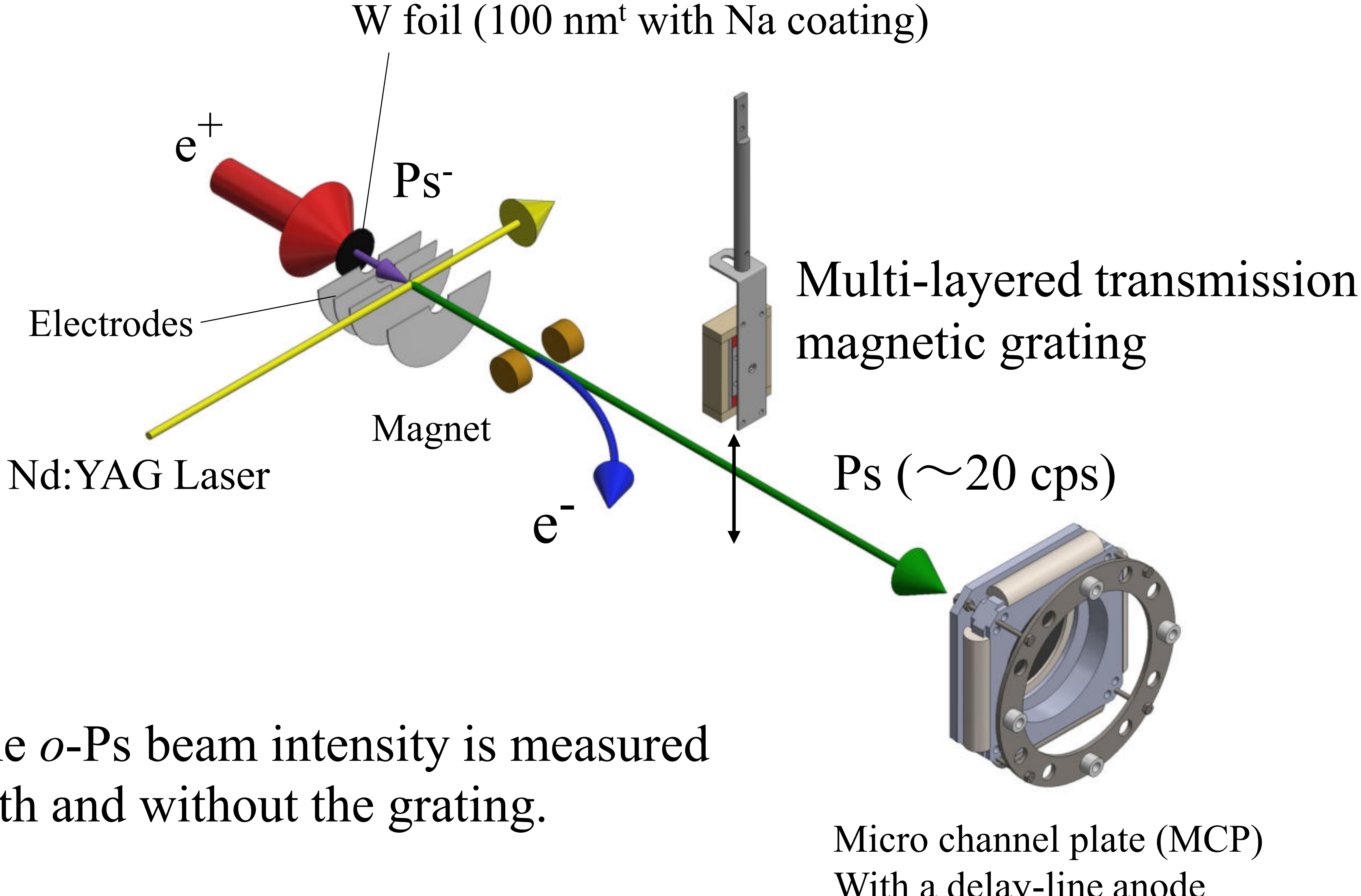
Pulse width (FWHM) : 2-10 ns
Frequency : 50 Hz
Intensity :10^{3}-10^{4} /shot
Beam diameter :1 mm

Ps- production region
P～1 × 10^{-8} Pa

Ps beamline [3]

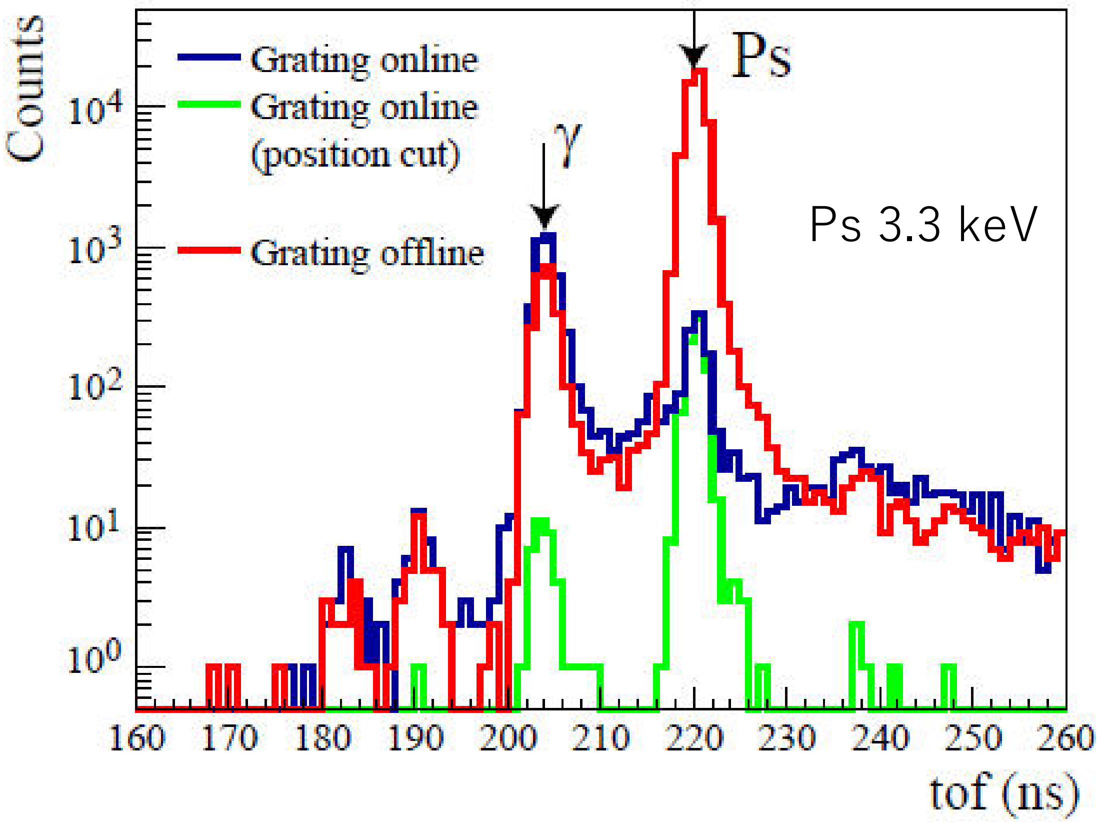
[1] A. P. Mills, Jr. and E. M. Gullikson, Appl. Phys. Lett. 49, 1121 (1986).
[2] C. M. Surko and R. G. Greaves, Physics of Plasmas 11, 2333 (2004);
[3] K. Michishio et al., Rev. Sci. Instrum., 90, 023305 (2019)

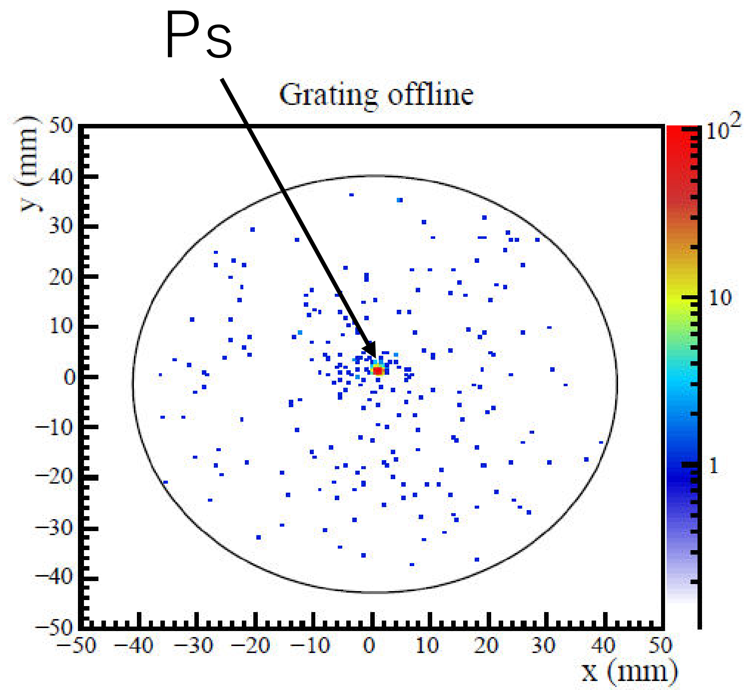
Main part of our experimental setup



The *o*-Ps beam intensity is measured with and without the grating.

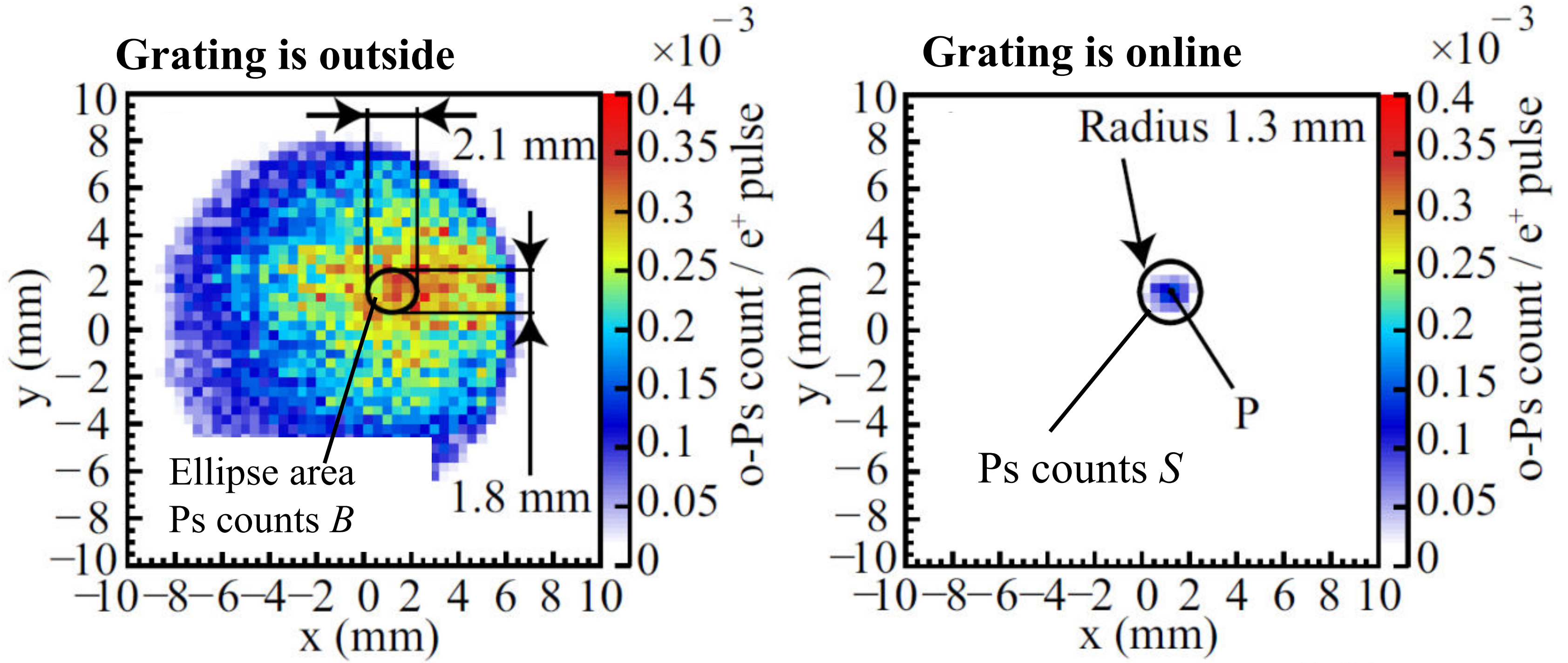
TOF spectra of MCP signals





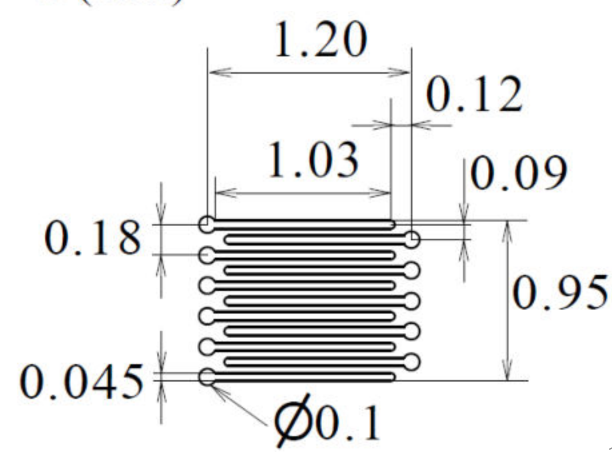
The γ ray background was decreased by a TOF cut and further decreased by a position cut.

Ps beam profiles



Normalized Ps counts = S / (B・A / C)

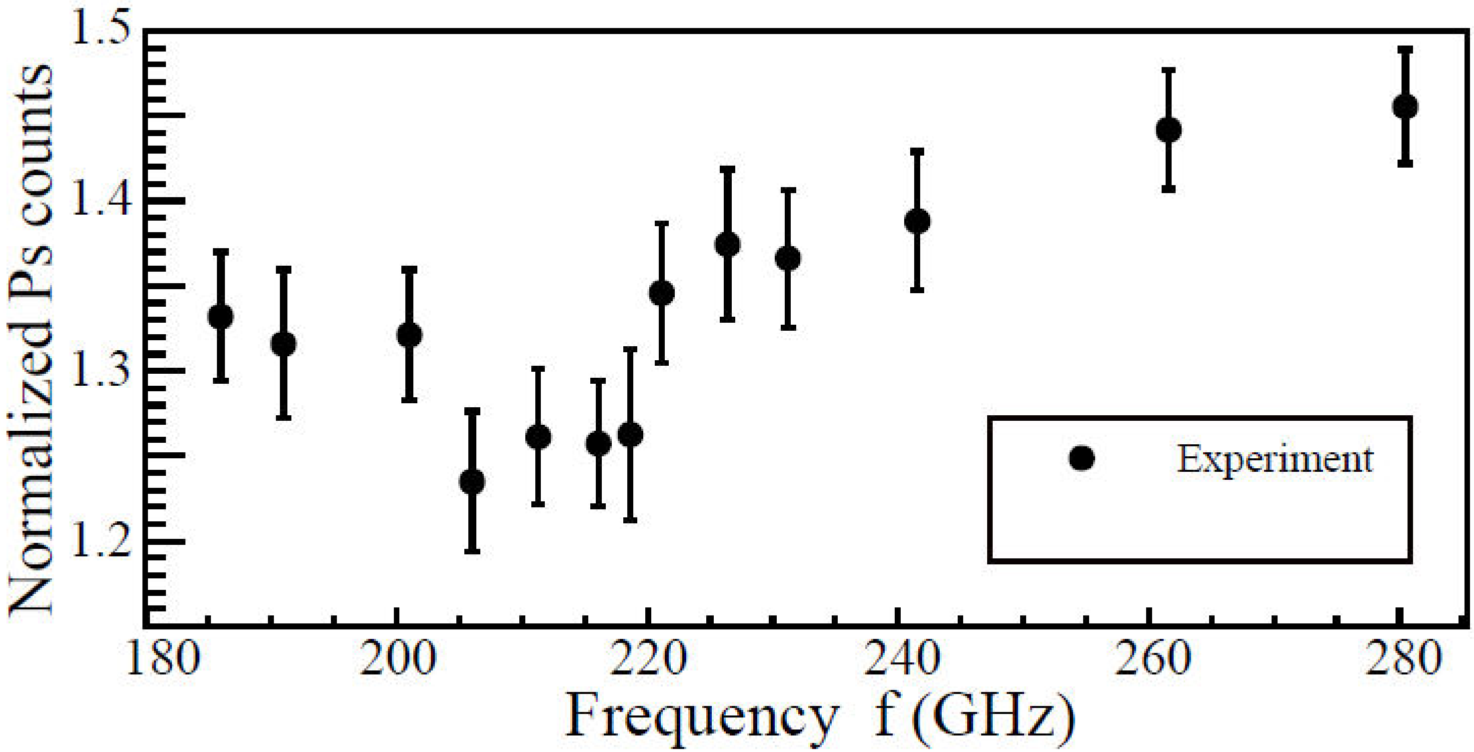
S: Signal counts
B: Background counts
A: Area of the slots
C: Area of the ellipse



Area of the slits

Y. Nagata et al., Phys. Rev. Lett. **124**, 173202 (2020)

Experimental results



(1) Resonance was observed at around 210 GHz.

(2) The counts have a slope.

(3) The counts exceed 1.

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Fit model

(1) Slope　(multi-hit events are removed)

- Number of multi-hit events ∝ Ps intensity ∝ $\boldsymbol{C\exp\left(-\frac{t}{479\ [\mathrm{ps}]}\right)}$

  (Ps⁻ lifetime τ=479 ps)

- $t = L/v,\quad v = fa,\quad B$: fit parameter

  L : effective length(between a W foil and a laser, 18 mm)

  a: period length, 86.4 um

  f: frequency of oscillating field

(2) Normalized counts > 1

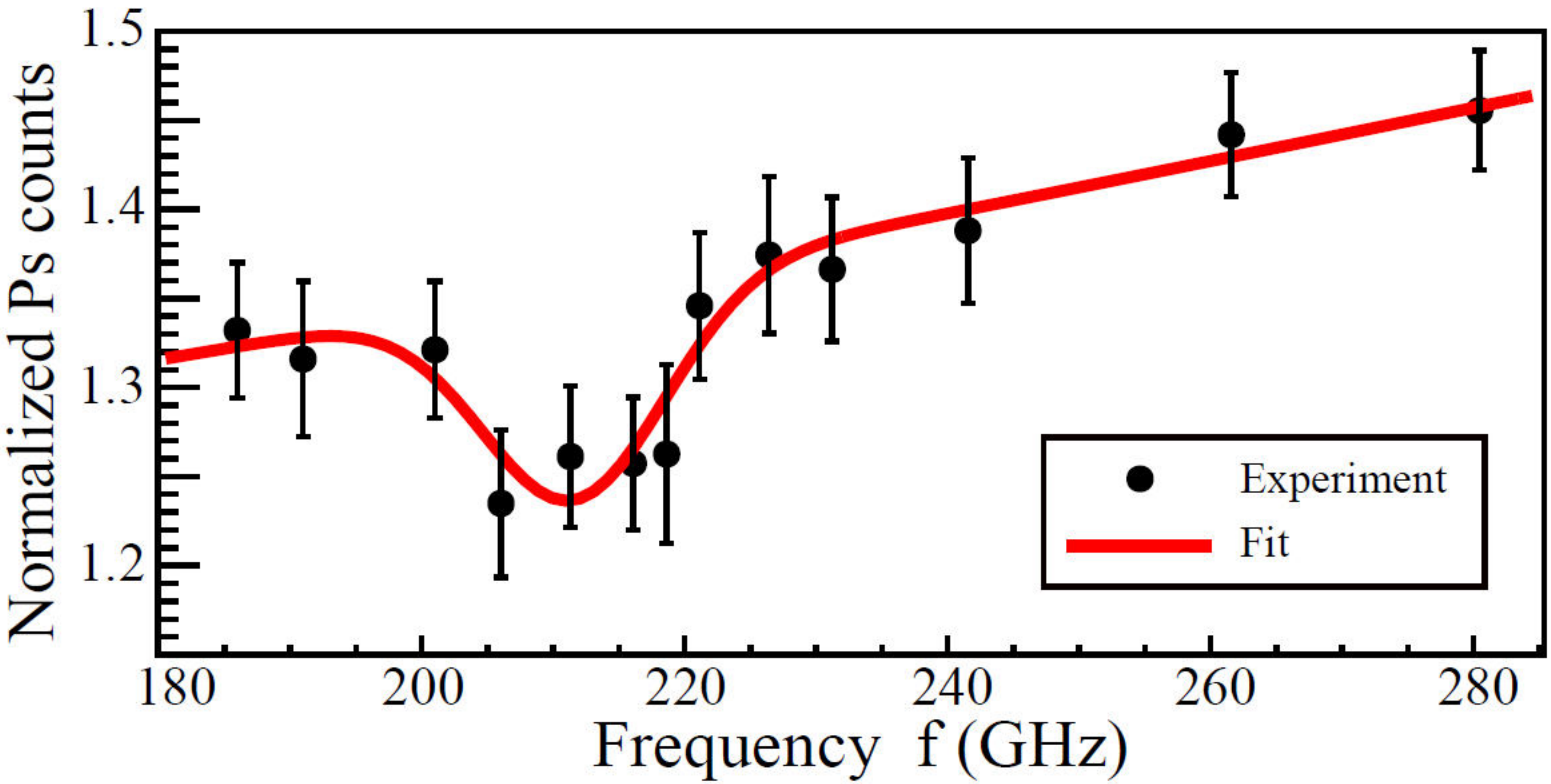
- Ps beam diverges gradually.
- Transmission efficiency is not determined precisely.
- Fit parameter ε

Fit model = ε (Gaussian +1) / slope function,

$$I(f) = \varepsilon\left(A\exp\left(-\frac{(f-f_0)^2}{2\sigma^2}\right)+1\right)\Big/\left(1-C\exp\left(-\frac{L}{fa\tau}\right)\right)$$

Fit parameter　$A, C, f_0, \sigma, \varepsilon$.

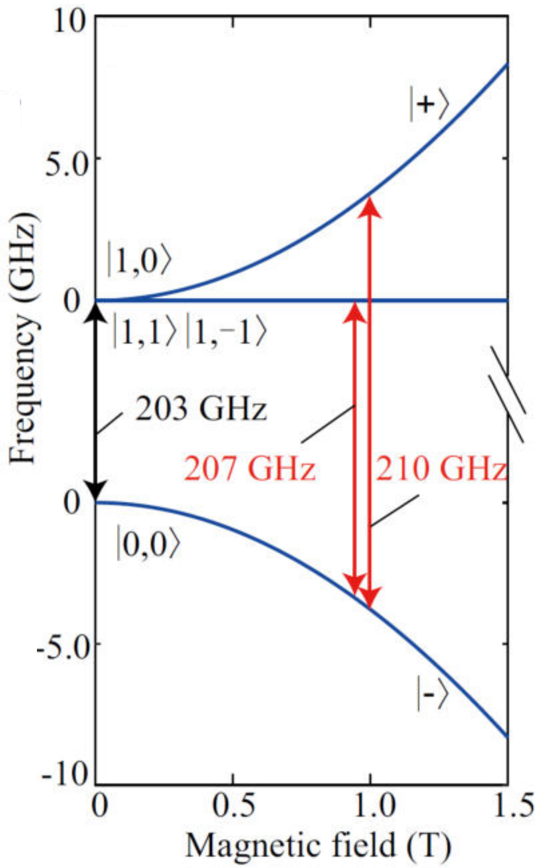
Experimental results



- Resonance center: 211.5 ± 1.9 GHz
- FWHM 16 ± 5 GHz (estimation: 210 GHz/10 ~21 GHz)

Y. Nagata et al., Phys. Rev. Lett. **124**, 173202 (2020)

Calculation of the transition from o-Ps to p-Ps



Basis set $|0,0\rangle,\ |1,1\rangle,\ |1,0\rangle\ |1,-1\rangle$

Density operator

$$\rho = \frac{1}{3}\,|1,1\rangle\,\langle 1,1| + \frac{1}{3}\,|1,0\rangle\,\langle 1,0| + \frac{1}{3}\,|1,-1\rangle\,\langle 1,-1|\,,$$

Hamiltonian

$$H_0 + H_1 = \begin{pmatrix} E_s & \sqrt{2}\mu_B B_x & -2\mu_B B_z & -\sqrt{2}\mu_B B_x \\ \sqrt{2}\mu_B B_x & E_t & 0 & 0 \\ -2\mu_B B_z & 0 & E_t & 0 \\ -\sqrt{2}\mu_B B_x & 0 & 0 & E_t \end{pmatrix}$$

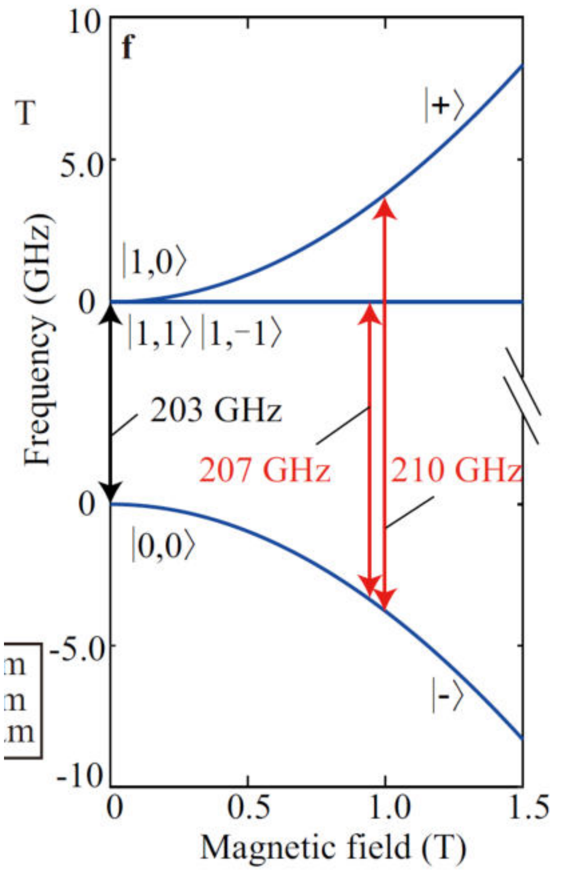
Schrödinger equation

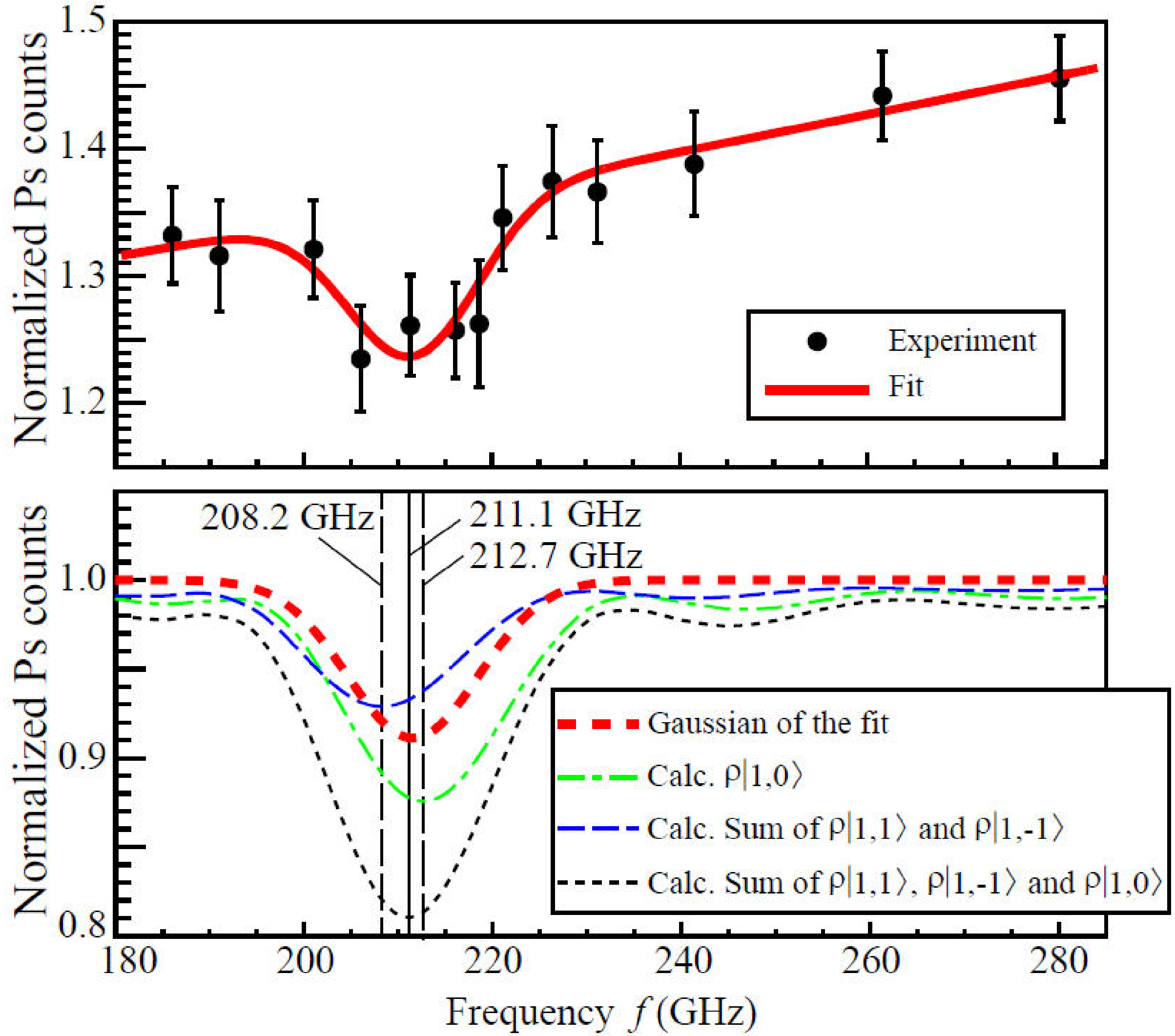
$$i\hbar\dot{\rho} = H\rho - \rho H - i\hbar L$$

$$L = \begin{pmatrix} \gamma_s\rho_{11} & \frac{\gamma_s+\gamma_t}{2}\rho_{12} & \frac{\gamma_s+\gamma_t}{2}\rho_{13} & \frac{\gamma_s+\gamma_t}{2}\rho_{14} \\ \frac{\gamma_s+\gamma_t}{2}\rho_{21} & \gamma_t\rho_{22} & \gamma_t\rho_{23} & \gamma_t\rho_{24} \\ \frac{\gamma_s+\gamma_t}{2}\rho_{31} & \gamma_t\rho_{32} & \gamma_t\rho_{33} & \gamma_t\rho_{34} \\ \frac{\gamma_s+\gamma_t}{2}\rho_{41} & \gamma_t\rho_{42} & \gamma_t\rho_{43} & \gamma_t\rho_{44} \end{pmatrix}$$

The time evolution of the density matrix was calculated.

Experimental results and calculations





- Resonance center: 211.5 ± 1.9 GHz (Calculation 211.1 GHz)

Y. Nagata et al., Phys. Rev. Lett. **124**, 173202 (2020)

Summary

Motion Induced Resonance of Ps hyperfine structure was observed for the first time by using energy-tunable Ps beams and a multi-layered magnetic grating.

Resonance Center was 211.5 $\pm$ 1.9 GHz (211.1 GHz in Calculation).

Resonance width (FWHM) was 16 $\pm$ 5 GHz.

Atomic physics

- First observation of MIR for exotic atoms in the sub-THz frequency region.

MIR techniques

- Strong static magnetic field of 0.12 T, corresponding to around 100 MW/cm^2.
- Magnetic dipole transition can be induced (electric dipole forbidden).

Applications

- Measurement of polarization in Zeeman levels of an *o*-Ps beam.
- Other Ps transitions.
- Other atomic and molecular system.

Thank you for your attention.

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