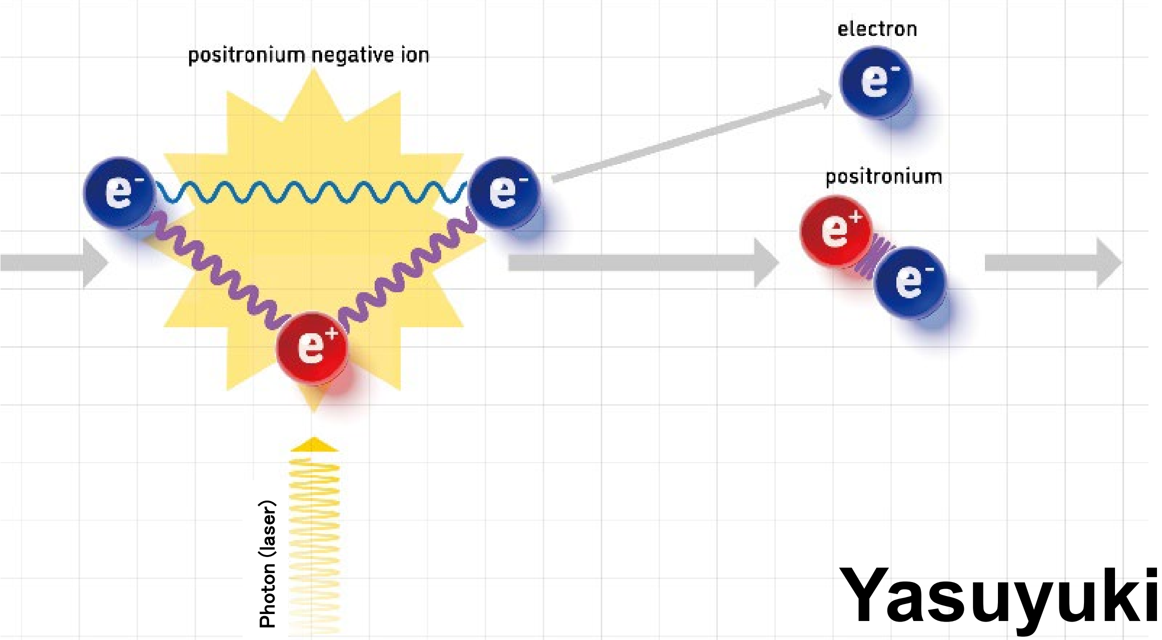
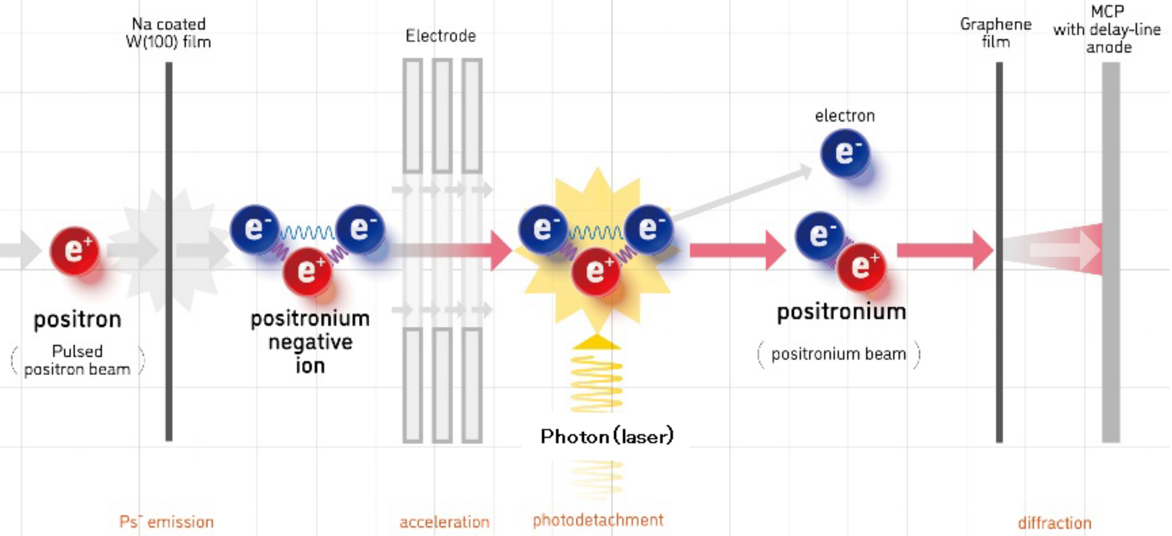
An energy-tunable positronium beam produced using photodetachment of positronium negative ions





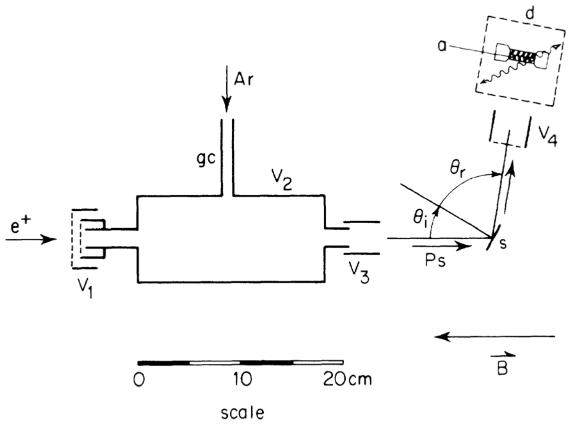
Yasuyuki Nagashima
Tokyo University of Science, Japan

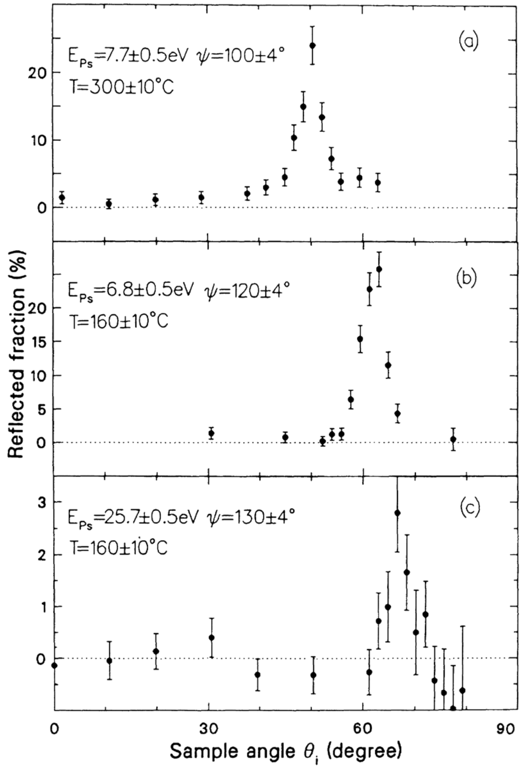
LEEPP 23 – 27 Mar. 2026
Jefferson Lab. USA

東京理科大学 TOKYO UNIVERSITY OF SCIENCE

Ps beam experiments

Ps specular reflection from LiF surface

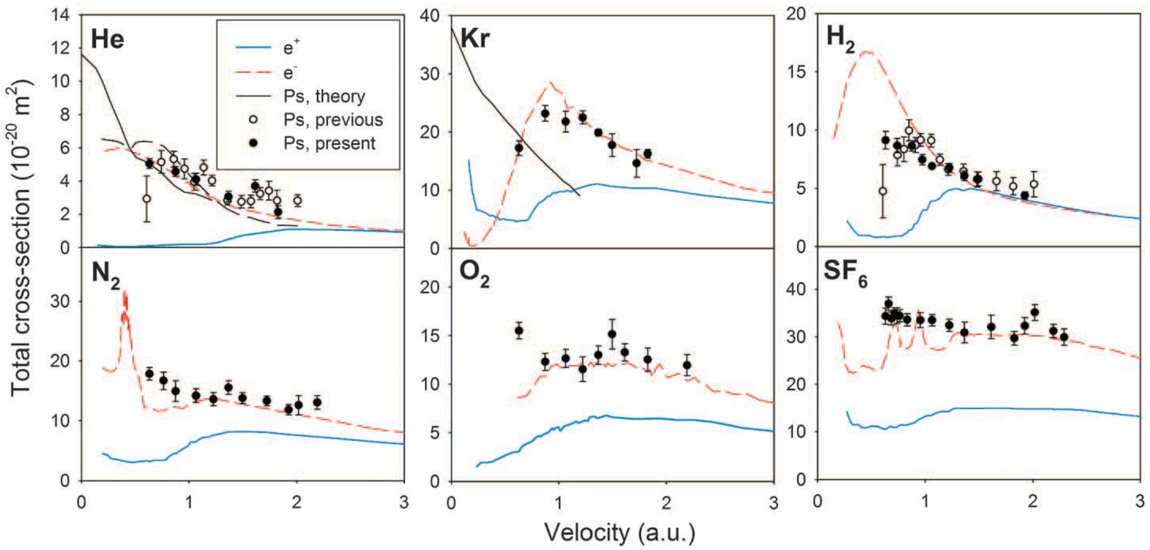




Ps specular reflection from LiF was observed.

Weber et al., PRL 61, 2542 (1988)

Ps total scattering cross sections from molecules were measured.



Electron-like scattering of Ps from molecules was observed.

Electrpn Brawley, Laricchia et al., Science 330, 789 (2010)

Ps beam experiments

PHYSICAL REVIEW LETTERS **136,** 033001 (2026)

Editors' Suggestion

Phase-Variation Ramsey Spectroscopy of the $2^3S_1 \rightarrow 2^3P_2$ Interval in Positronium

D. M. Newson and D. B. Cassidy

Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, United Kingdom

(Received 7 October 2025; accepted 2 January 2026; published 22 January 2026)

The $2\,^3S_1 \rightarrow 2\,^3P_2$ interval (ν_2) in positronium has been measured using a phase-variation separated oscillatory fields technique. A beam of positronium atoms in the $2\,^3S_1$ state was passed through two spatially separated coherent microwave fields tuned close to the ν_2 resonance frequency (8626.71 ± 0.08 MHz), and the surviving beam fraction was recorded as a function of the relative phase between the fields. The resonance frequency was obtained from the frequency dependence of the phase of the interference signal without scanning over the full spectral line shape of the transition. We obtain $\nu_2 = 8626.39 \pm 1.17_{\mathrm{stat}} \pm 0.80_{\mathrm{sys}}$ MHz, which is in agreement with QED theory.

Development of energy tunable Ps beams is an important task for the researchers in this field.

Ps is electrically neutral. → It is difficult to accelerate Ps.

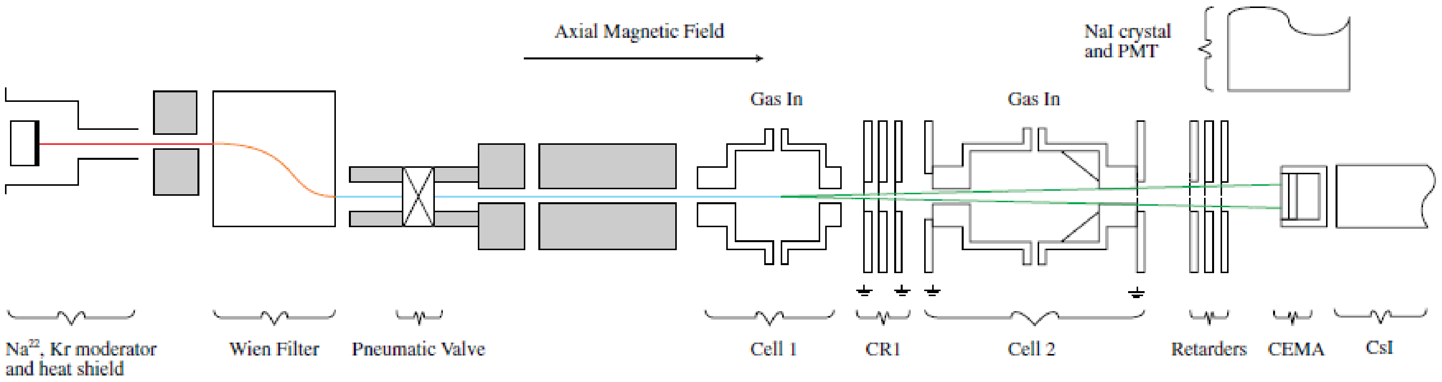
Ps beam production by neutralization of accelerated monoenergetic e^+ through gases

e^+ → gas → Ps

Ps energy $= E_0 - I + 6.8$ eV,
where E_0 is the positron energy
and I is the ionization energy of the gas atom.

→ Ps-atom/molecule scattering

(B. L. Brown (Bell Lab.), G. Laricchia, D. Cassidy et al. (UCL))



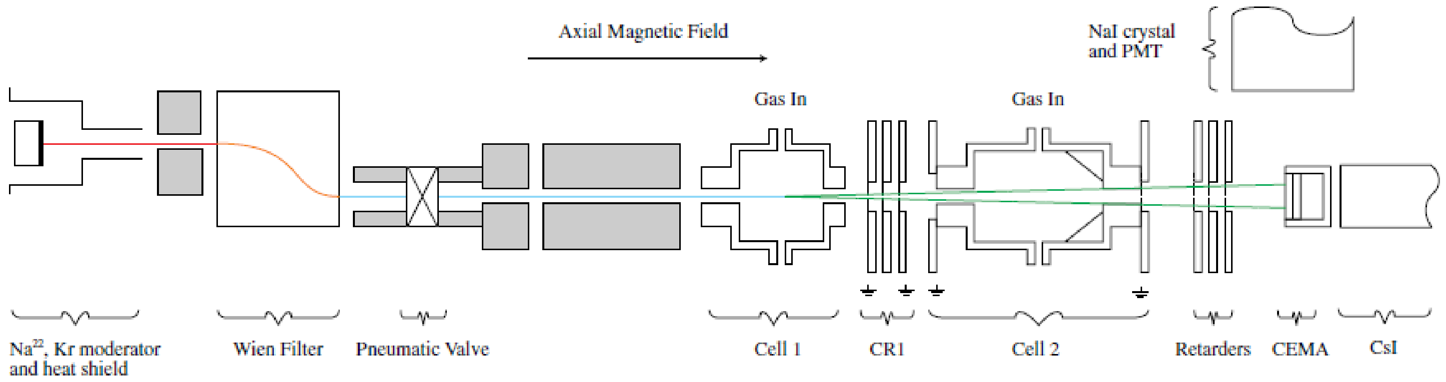
Zafar et al., PRL 76, 1595 (1996), Brawley et al., PRL 105, 263401 (2005)

Development of energy tunable Ps beams is an important task for the researchers in this field.

Ps is electrically neutral. → It is difficult to accelerate Ps.

Ps beam production by neutralization of accelerated monoenergetic e^+ through gases

For the Ps beam experiments which need ultra-high vacuum condition, Ps beams produced without gases must be developed.



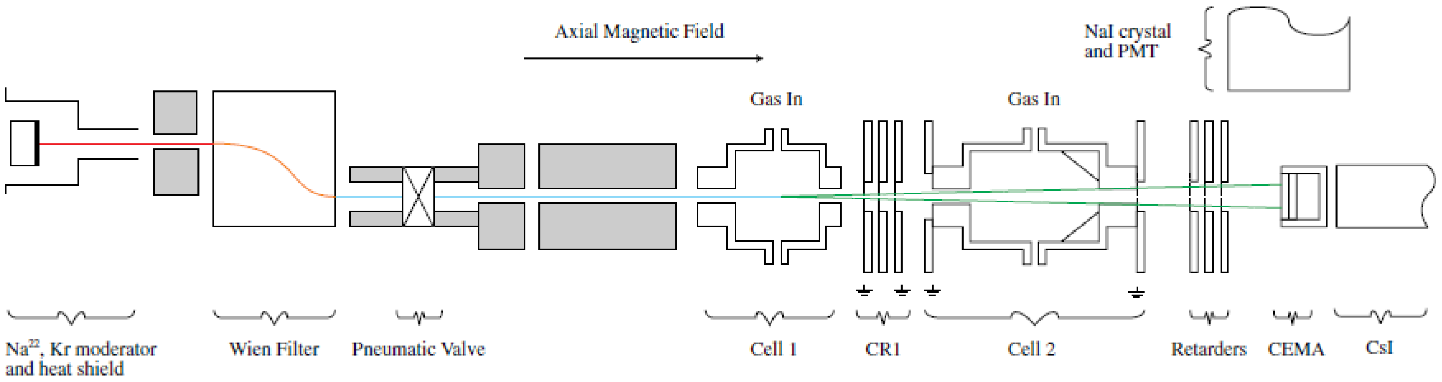
Zafar et al., PRL 76, 1595 (1996), Brawley et al., PRL 105, 263401 (2005)

Development of energy tunable Ps beams is an important task for the researchers in this field.

Ps is electrically neutral. ⇨ It is difficult to accelerate Ps.

Ps beam production by neutralization of accelerated monoenergetic e^+ through gases

In the course of our research on Ps^-, we have succeeded in generating a new type of energy tunable Ps beam and we are now expanding our research.



Zafar et al., PRL 76, 1595 (1996), Brawley et al., PRL 105, 263401 (2005)

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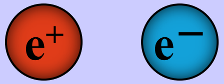
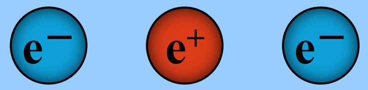
positronium (Ps)



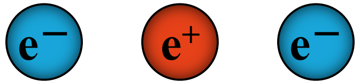
- ✓ H atom like state
- ✓ Lightest “atom”
- ✓ Binding energy : 6.80eV
- ✓ Mean distance $e^+ - e^-$ of ground state Ps : $3a_0$
- ✓ Two eigenstates
  - Ortho-Ps (S=1, triplet)
    - Lifetime in vacuum : 142ns
    - Self-annihilates into 3γ .
  - Para-Ps (S=0, singlet)
    - Lifetime in vacuum : 125ps
    - Self-annihilates into 2γ .
- ✓ There are many excited states.

positronium negative ion (Ps^-)



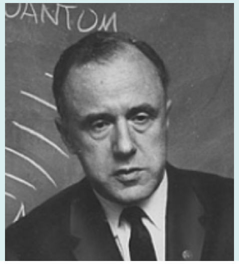
- ✓ H^- ion like state
- ✓ Simplest three body system
- ✓ e^- binding energy to Ps : 0.33eV
  The energy required to break up into 3 isolated particles : 7.13eV
- ✓ Mean distance $e^+ - e^-$: $5.5a_0$
- ✓ Only one state
  - Lifetime in vacuum : 479ps
  - Self-annihilates into 2γ.
- ✓ There are no excited states.

Discovery of the Ps^-



"The tri-electron system has a radioactive mean lifetime of the order of 10^{-10} sec, and is calculated to be stable by at least 0.19eV against dissociation into a bi-electron and a free electron or positron."

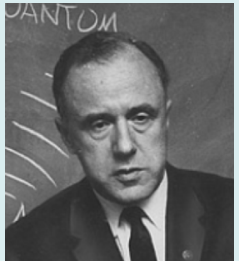
"For the formation of an entity of the type P^{+--}, the most reasonable mechanism appears to be the interaction of a photon with an atomic electron." (John Wheeler)



(Wheeler, Ann. New York Acad. of Sci. 3 (1946) 219)

Discovery of the Ps^- e^- e^+ e^-

"The tri-electron system has a radioactive mean lifetime of the order of 10^{-10} sec, and is calculated to be stable by at least 0.19eV against dissociation into a bi-electron and a free electron or positron."
"For the formation of an entity of the type P^{+--}, the most reasonable mechanism appears to be the interaction of a photon with an atomic electron." (John Wheeler)



(Wheeler, Ann. New York Acad. of Sci. 3 (1946) 219)

First observation : performed by Allen Mills, Jr. in 1981.

(Mills, PRL 46 (1981) 717)

Allen Mills, Jr.

e^+ → | → Ps^-

carbon foil

Formation efficiency ~ 0.028%

Further experimental investigations were limited only to the measurement of its lifetime.

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✔ Positron annihilation in materials is "slow".

Positron annihilation cross section: $\sigma_+ = \frac{\pi r_0^2}{\gamma+1}\left[\frac{\gamma^2+4\gamma+1}{\gamma^2-1} ln\left(\gamma + \sqrt{\gamma^2-1}\right) - \frac{\gamma+3}{\sqrt{\gamma^2-1}}\right]$ (Dirac, 1930; Heitler 1957)

$\gamma = 1/\sqrt{1-\beta^2}, \beta = v/c$
v: speed of the positron

$r_0 = e^2/(4\pi\epsilon_0 mc^2) = 2.8 \times 10^{-15}$ m (classical electron radius) $\ll$ a_0 (0.053 nm)

When $v \ll c$, $\sigma_+ = \pi r_0^2 c/v$.

$\sigma_+ \ll$ scattering cross section

Positrons incident on solids are thermalized in a few ps, exhibit behaviors specific to the thermalized positrons while they diffuse in the bulk, and eventually annihilate with surrounding electrons.

Positron annihilation rate: $\Gamma = n\sigma_+ v = \pi r_0^2 cn$
n: electron density

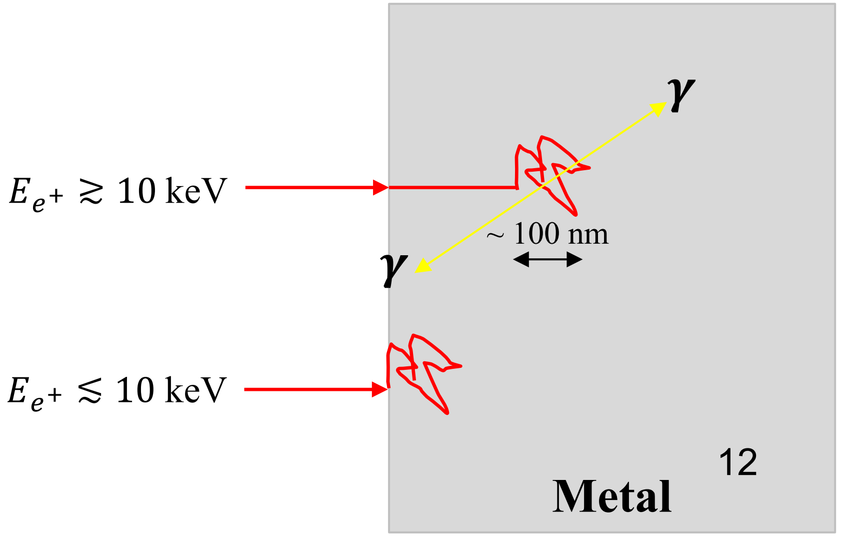
Positron mean lifetime in metals: $\tau = 1/\Gamma \sim 100$ ps

✔ Positron diffusion length in metals is ~ 100 nm.

When $E_{e^+} \gtrsim$ 10keV, most positrons annihilate in the bulk.

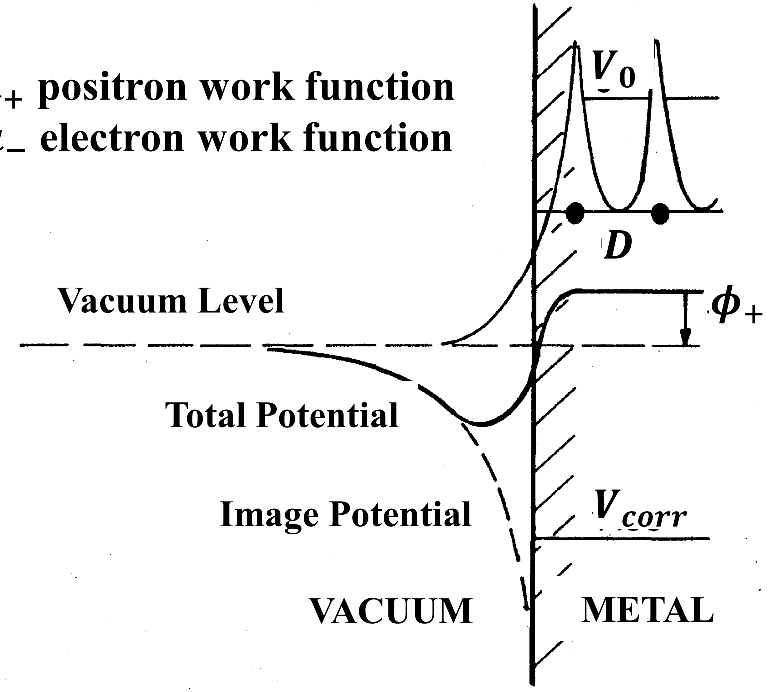
When $E_{e^+} \lesssim$ 10 keV, a significant fraction of the positrons diffuse back to the surface, and

surface-specific phenomena occur.

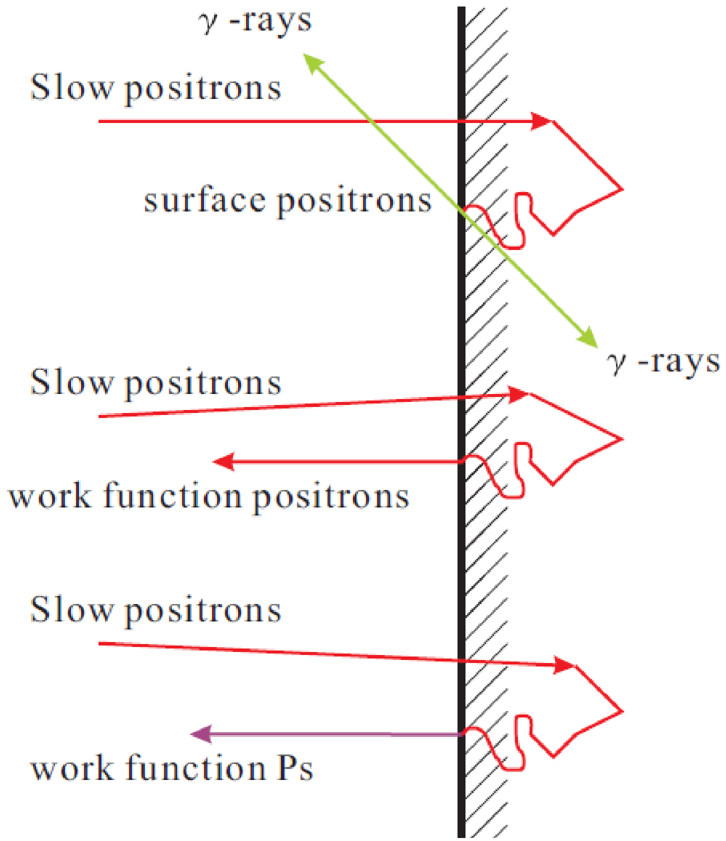


Ps emission from metal surfaces

$\phi_+ = D_+ - \mu_+$ **positron work function**
$\phi_- = D_- - \mu_-$ **electron work function**



The single-particle potential
for thermalized positrons near metal surface
(Schultz and Lynn, RMP 1988)



Fates of slow positrons incident on metal surface

The energy required for Ps emission
(Ps work function)

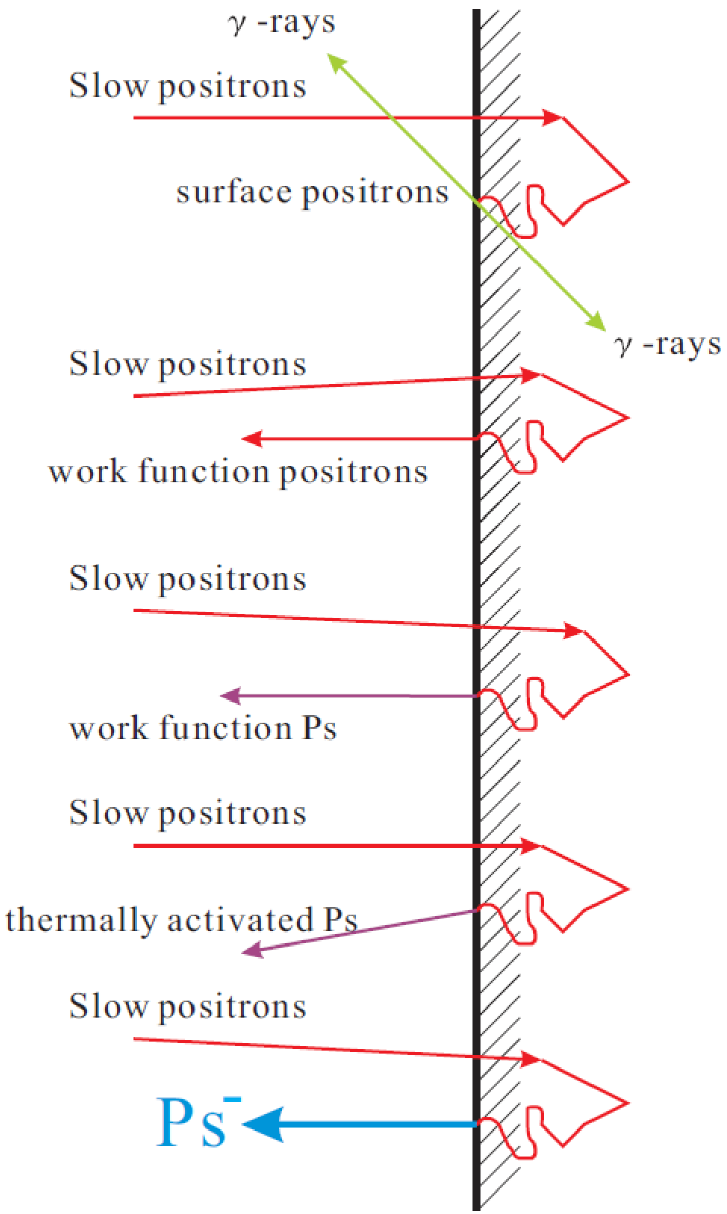
$$\phi_{Ps} = \phi_+ + \phi_- - 6.80 \text{ eV}$$

e+ work function

e− work function

If $\phi_{Ps} < 0$, Ps is emitted from the surface.

Ps^- emission from metal surfaces



The energy required for Ps^- emission (Ps^- affinity) :

$$\phi_{Ps^-} = \phi_+ + 2\phi_- - 7.13\,\text{eV}$$

e^- work function

e^+ work function

The energy required to break up Ps^- into three isolated particles
=(Ps binding energy, 6.80eV)
+(e^- binding energy to Ps, 0.33eV)

If $\phi_{Ps^-} < 0$,

⇩

Ps^- may be emitted
from the surface spontaneously.

(Wilson and Mills, Phys. Rev. B 27, 3949 (1983))

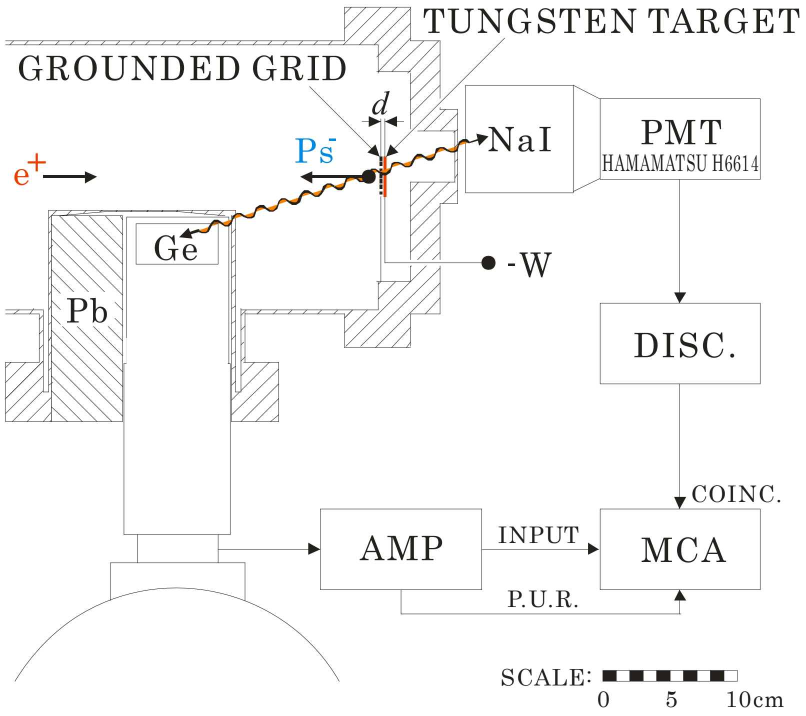
Element	Φ_+ (eV)	Φ_- (eV)	Φ_{Ps-} (eV)
Al (polycrystalline)	-0.2	4.25	1.2
Al (1 0 0)	-0.16	4.20	1.11
Al (1 1 1)	0.065	4.26	1.46
Cr (1 0 0)	-1.76	4.46	0.03
Fe (polycrystalline)	-1.2	4.4	0.5
Co (polycrystalline)	-0.8	5.0	2.1
Ni (polycrystalline)	-1.2	5.15	2.0
Ni (1 0 0)	-1.0	5.22	2.3
Ni (1 1 0)	-1.4	5.04	1.6
Cu (1 0 0)	-0.3	5.10	2.8
Cu (1 1 0)	-0.2	4.48	1.6
Cu (1 1 1)	-0.4	4.94	2.4
Mo (polycrystalline)	-2.2	4.6	*-0.1*
Mo (1 0 0)	-1.7	4.53	0.2
Ag (1 0 0)	0.6	4.64	2.8
W (polycrystalline)	-2.75	4.55	*-0.78*
W (1 0 0)	-3.0	4.63	*-0.9*
W (1 1 0)	-3.0	5.22	0.3
W (1 1 1)	-2.59	4.45	*-0.82*
Pt (polycrystalline)	-1.8	5.64	2.4
Au (polycrystalline)	0.9	5.2	4.2
Pb (polycrystalline)	0.9	4.25	2.3

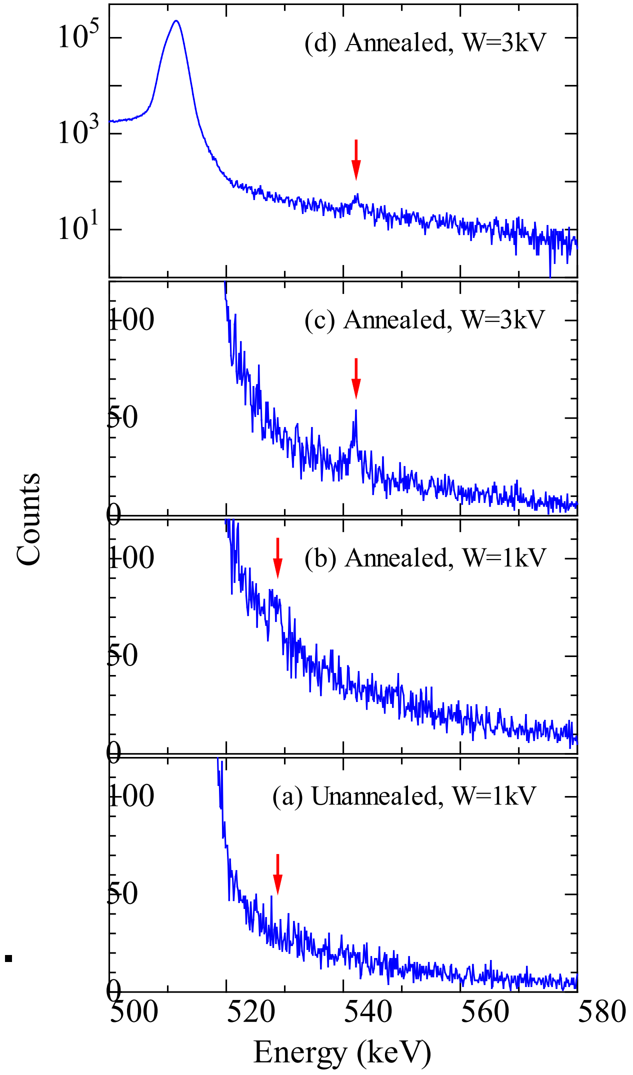
Nagashima, Phys. Rep. 545, 95 (2014)

✓ polycrystalline molybdenum
✓ tungsten (1 0 0)
✓ tungsten (1 1 1)
✓ polycrystalline tungsten

Ps^- ions may be emitted.

Ps⁻ emission from polycrystalline tungsten surface





Ps⁻ emission efficiency was only 0.01% or less.

Nagashima and Sakai, NJP 8 (2006) 319

Effect of Cs coating for the Ps⁻ emission

$$\phi_+ = -\mu_+ - D$$

$$\phi_- = -\mu_- + D$$

μ_+ : e^+ chemical potential (bulk effect)
μ_- : e^- chemical potential (bulk effect)
D : effect of surface dipole (surface effect)

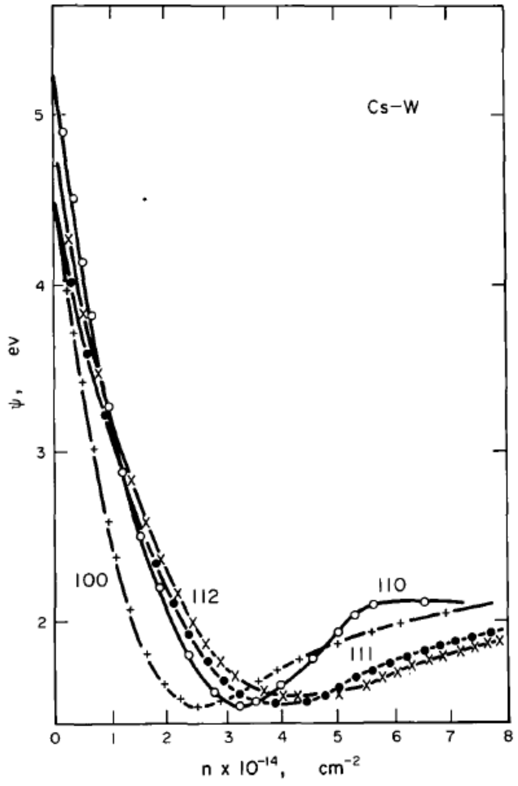
$$\phi_{Ps^-} = -\mu_+ - 2\mu_- + D - 7.13\,\mathrm{eV}$$

D **decreases by Cs coating.**

ϕ_{Ps^-} decreases.

Ps⁻ emission efficiency may increase.

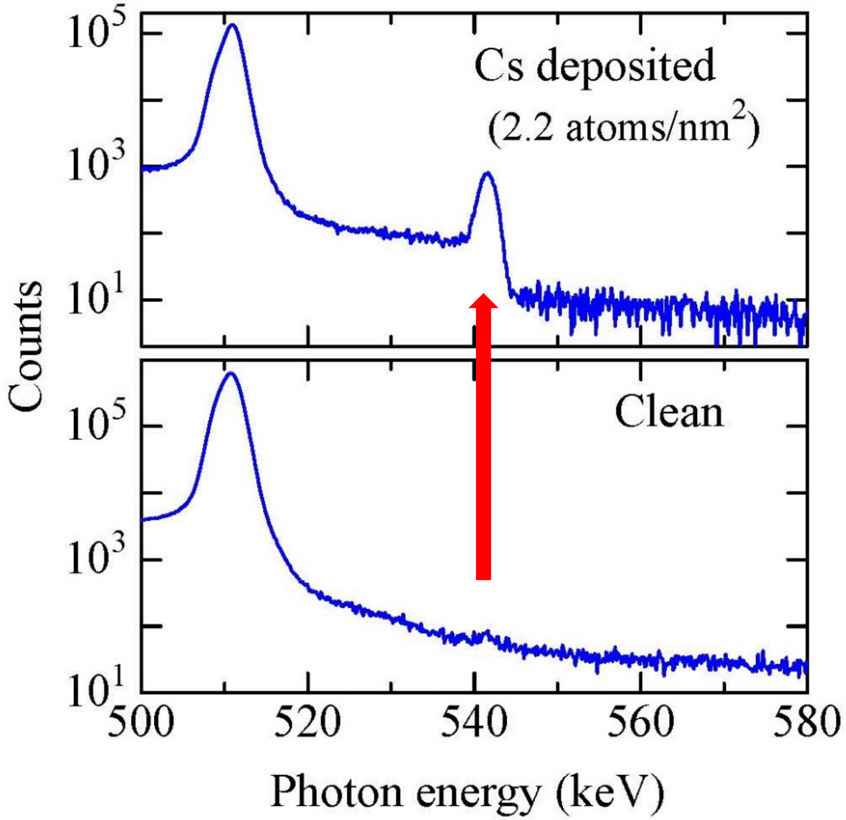
Change of ϕ_- for tungsten by Cs coating



D **decreases.**

Kiejna and Wojciechowski,
Prog. in Surf. Sci. 11 (1981) 293

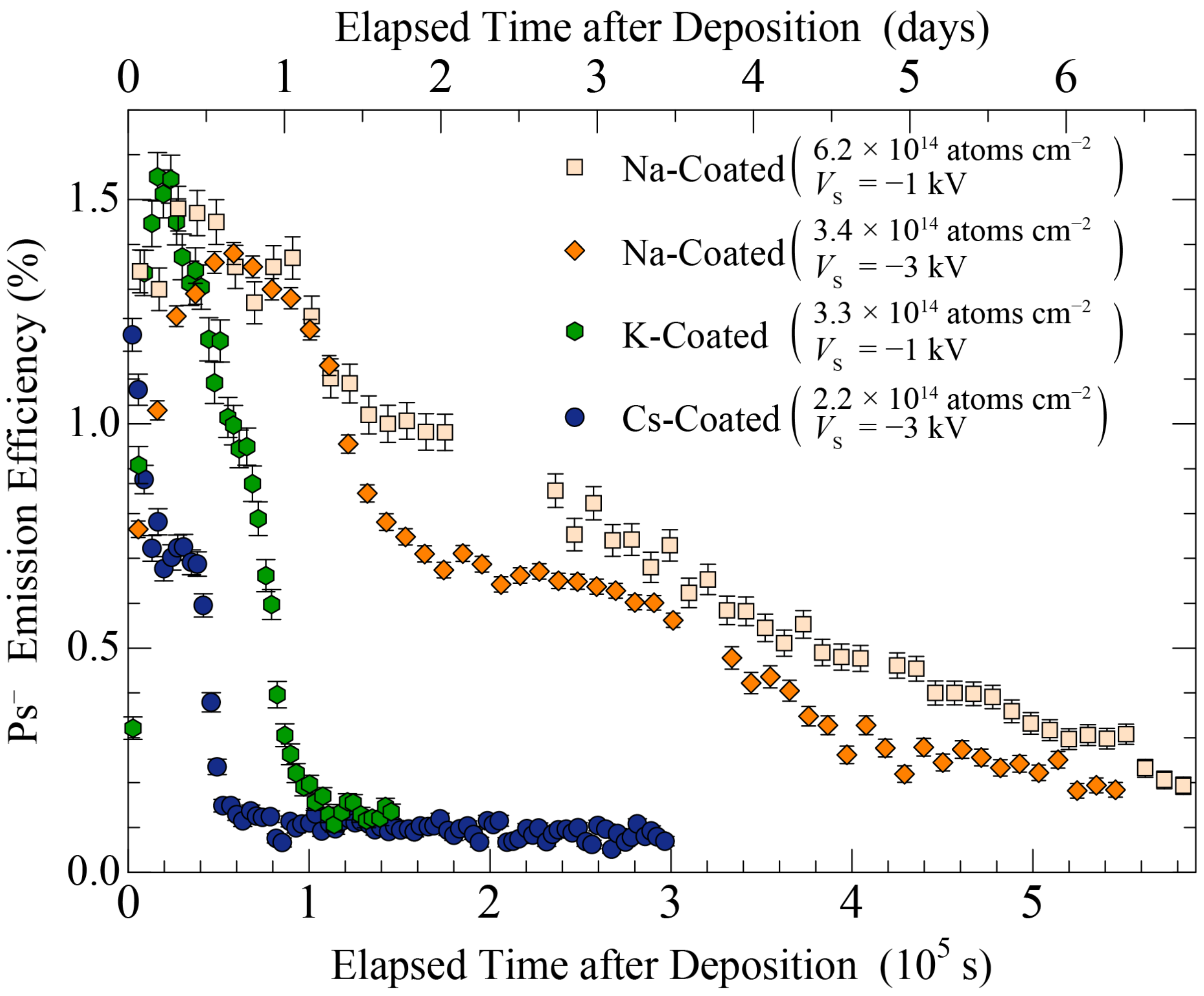
Ps^- emission from Cs deposited W(100)



The efficiency was
1.25 %,
which is two orders of magnitude higher than that obtained for uncoated surface, and 45 times greater than the beam-foil method.

Nagashima et al., Phys. Rep. 545, 95 (2014)

Time dependence of Ps^- emission efficiency for tungsten coated with several alkali metals @ $2x10^{-8}$ Pa



Na is the best alkali metal for the Ps^- production.

Ps^- branching ratio ~ 2%

Terabe, Michishio, Tachibana and Nagashima, NJP 14 (2012) 015003

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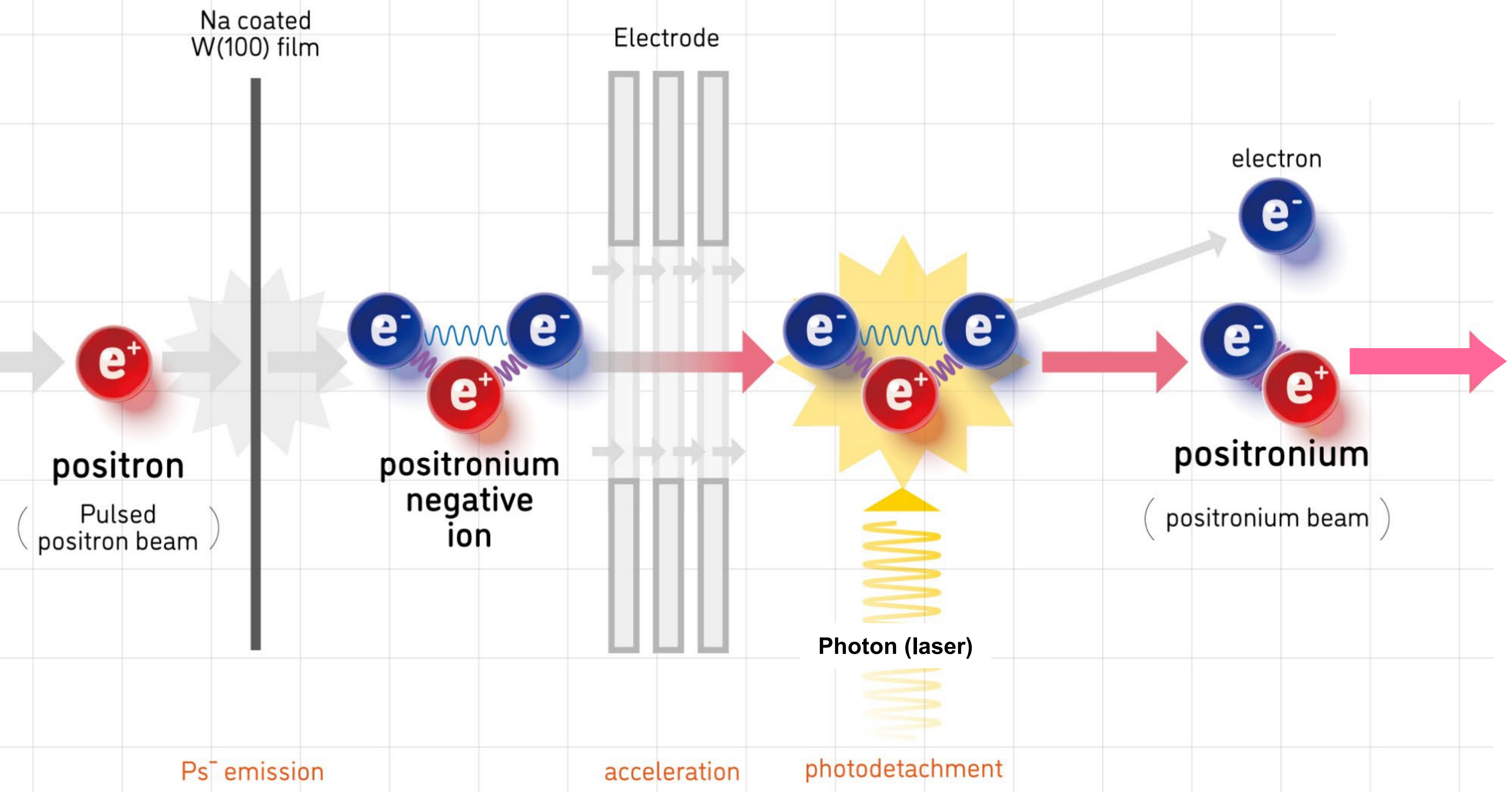
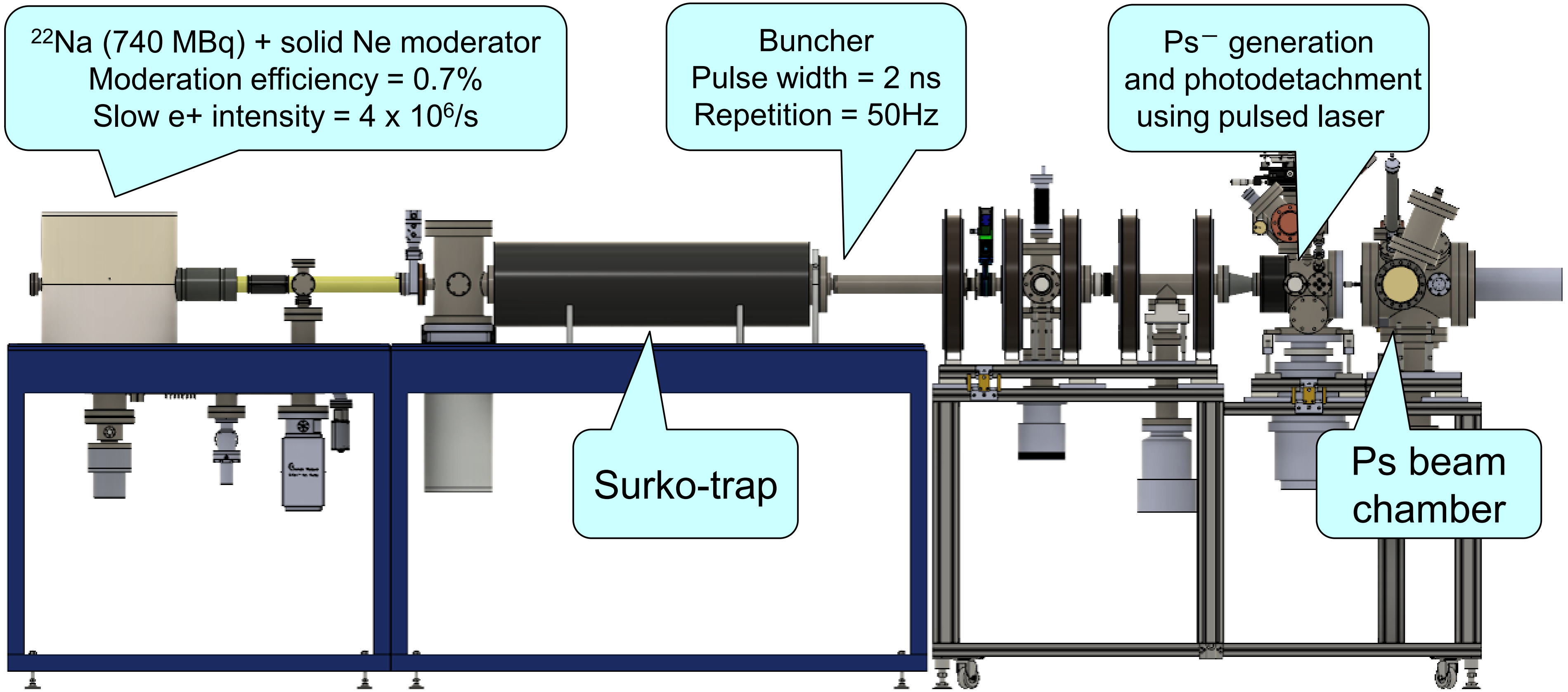
Ps beam produced by the photodetachment of Ps^- using a thin tungsten foil

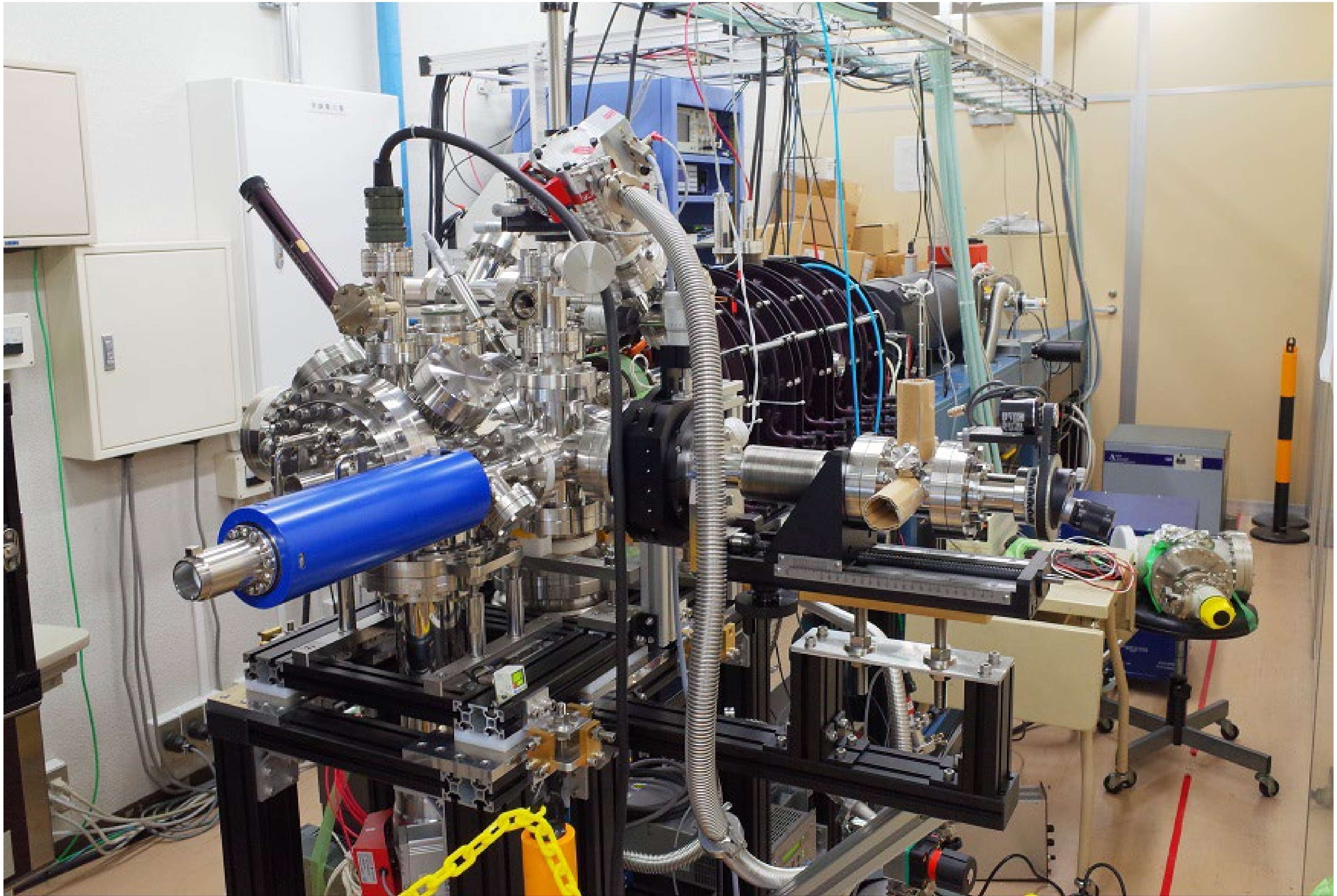


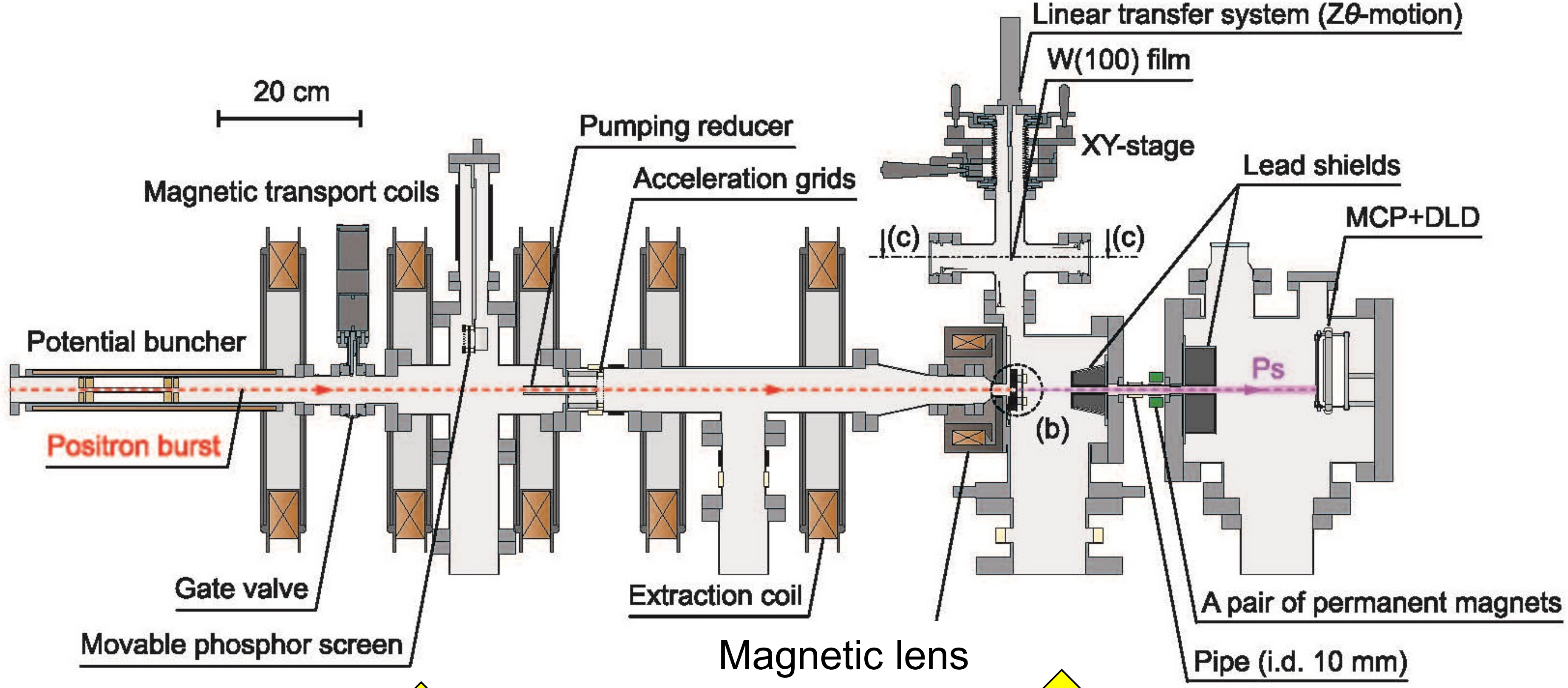
Energy tunable Ps beam via photodetachment of accelerated Ps⁻



Michishio et al., RSI 90, 023305 (2019)

Energy tunable Ps beam via photodetachment of accelerated Ps^-

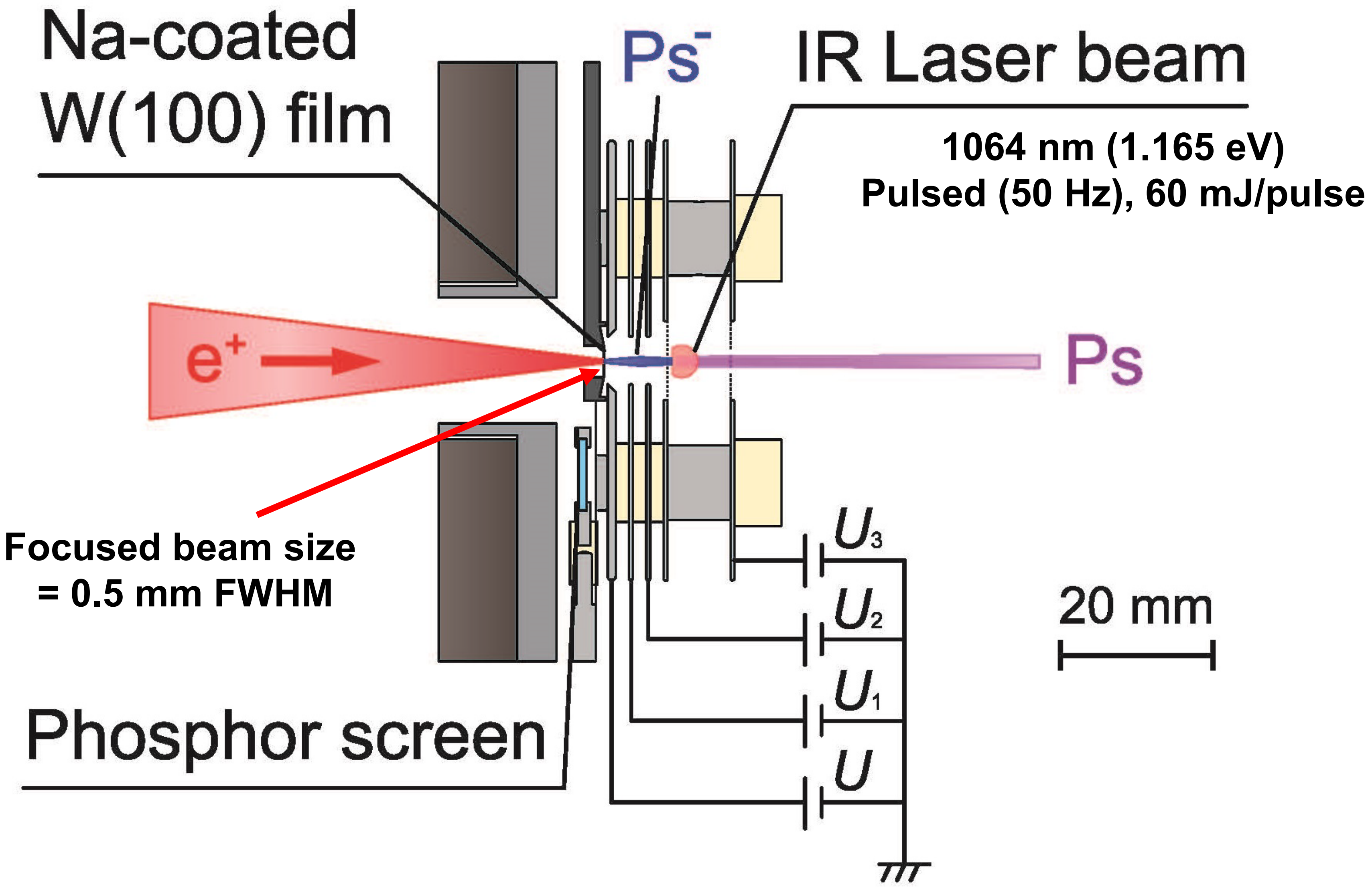


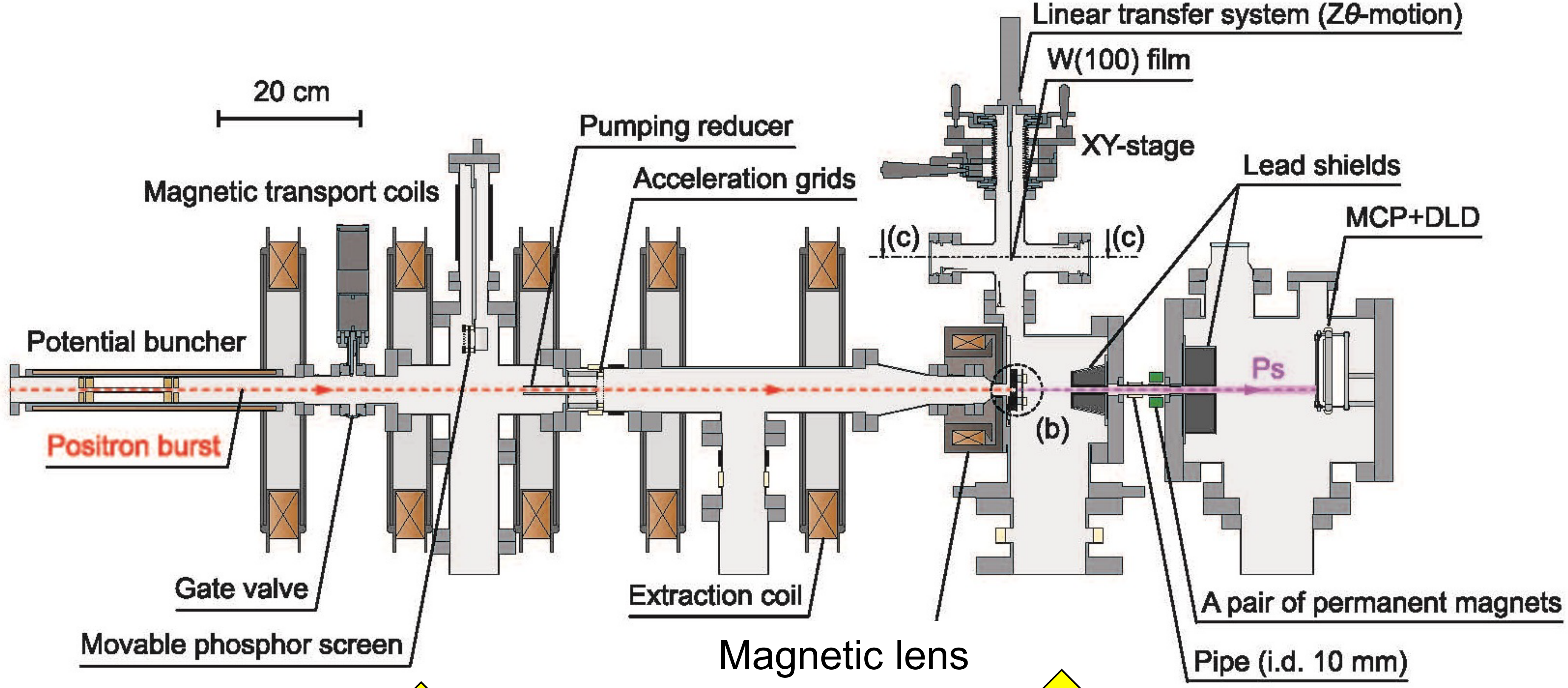


Ps production chamber

Pulsed positron transport line
to avoid gas flow from the positron trap

Michishio et al., RSI 90, 023305 (2019)


Na-coated
W(100) film
Ps⁻
IR Laser beam
1064 nm (1.165 eV)
Pulsed (50 Hz), 60 mJ/pulse
e⁺
Ps
Focused beam size
= 0.5 mm FWHM
U3
U2
U1
U
20 mm
Phosphor screen



Magnetic lens

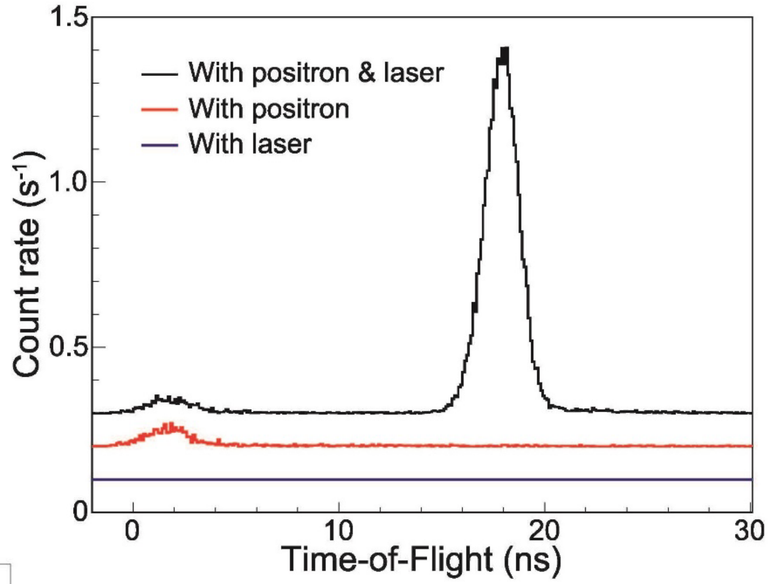
Ps production chamber

Pulsed positron transport line
to avoid gas flow from the positron trap

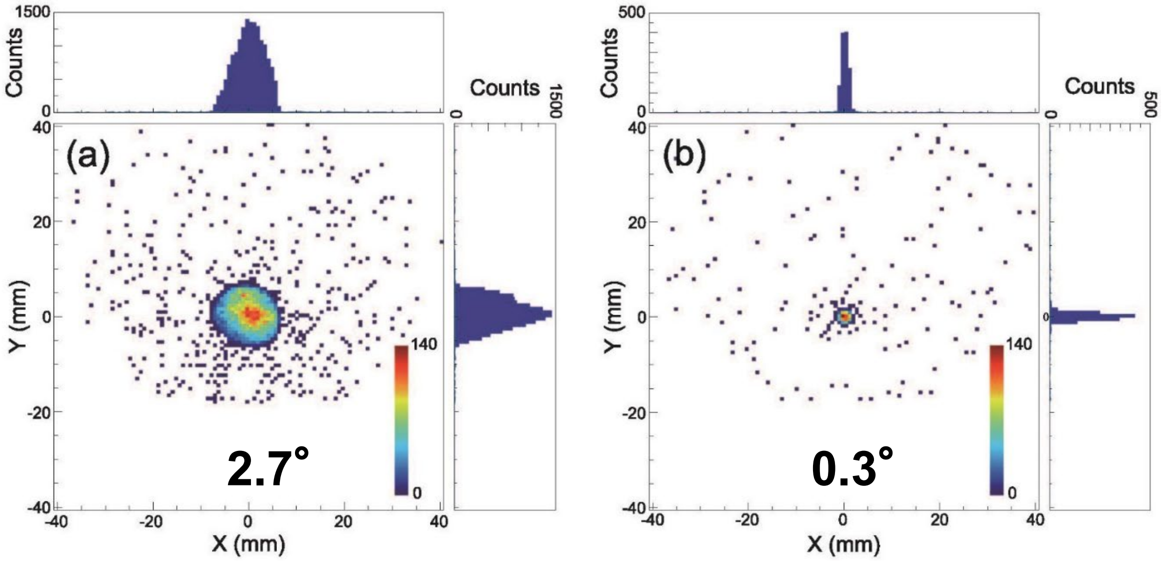
Michishio et al., RSI 90, 023305 (2019)

Specifications of the Ps beam in TUS

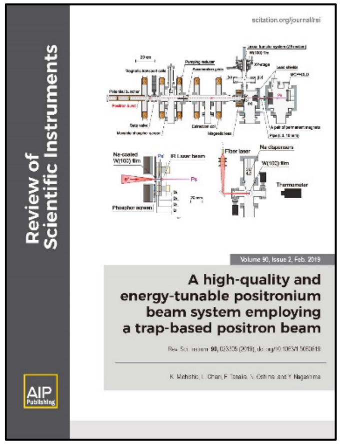
Ps energy : 0.3 – 3.3 keV
Ps count rate : 23 cps (Detection efficiency included)
Ps beam diameter : 9mm
If we use an aperture with a 1 mm hole, angular divergence is reduced to be 0.3° accordingly.



Ps TOF spectra



Ps beam spots



Cover of Rev. Sci. Instrum.

Michishio et al., RSI 90 (2019) 023305 (Scilight, featured)

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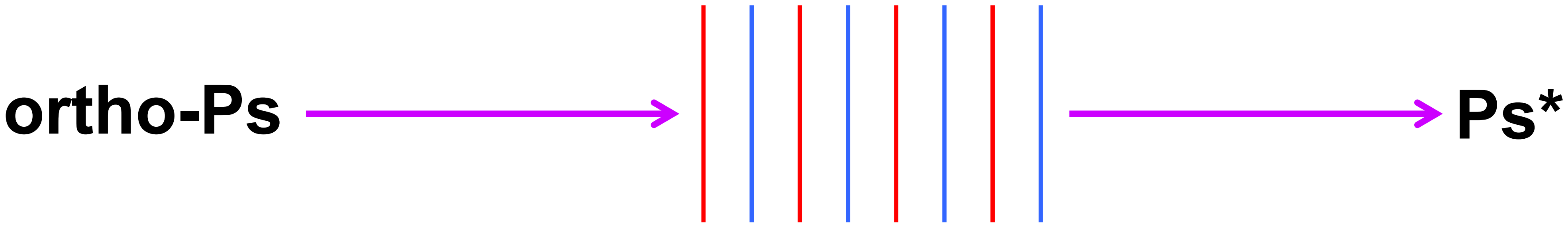
Observation of Resonant Coherent Excitation (RCE) of ortho-Ps



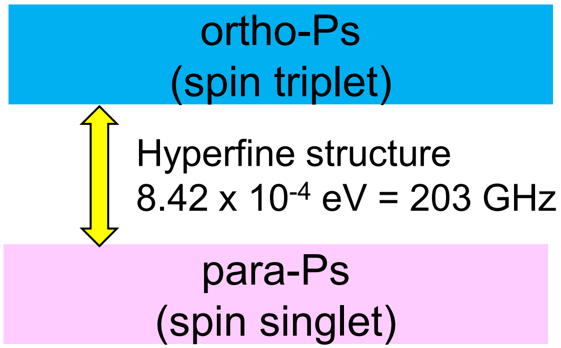
The effect of periodic potential is equivalent to laser irradiation.

ortho-Ps may be excited, or deexcited.

Ps hyperfine structure:

difference of energy levels of o-Ps and p-Ps = 8.42 x 10^{-4} eV = 203 GHz

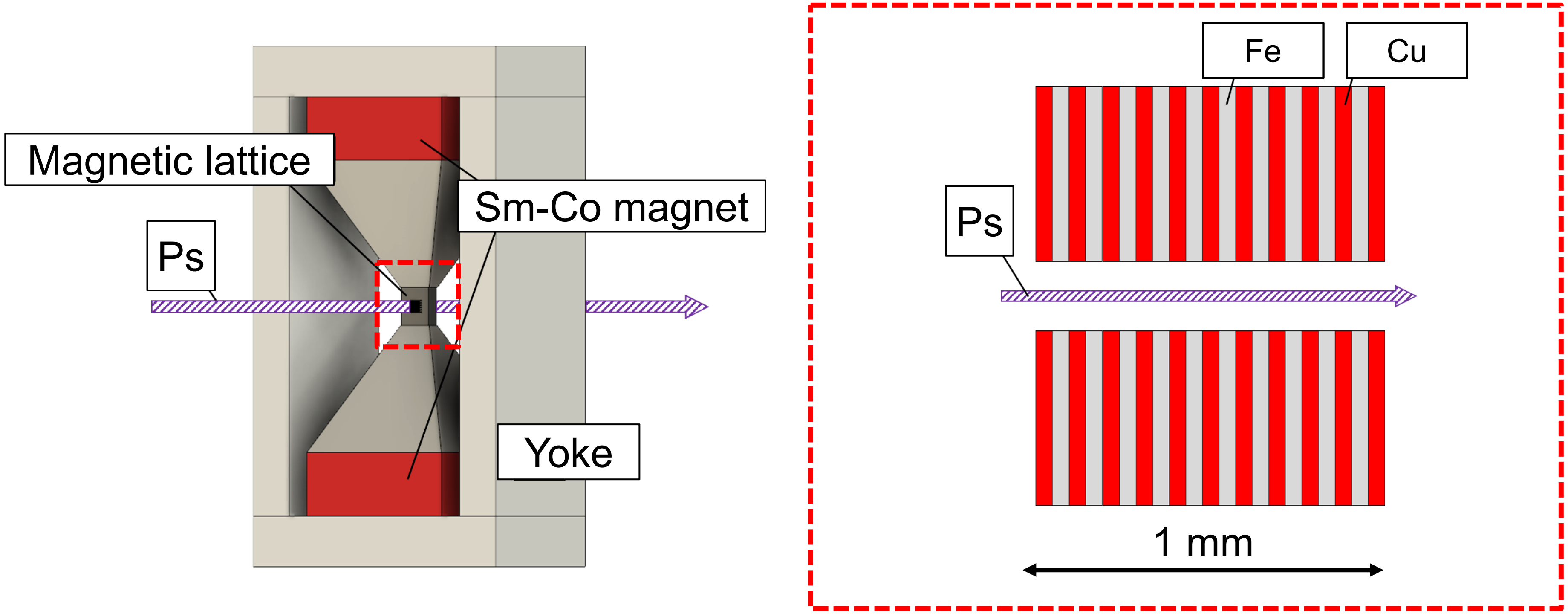
Optically forbidden transition

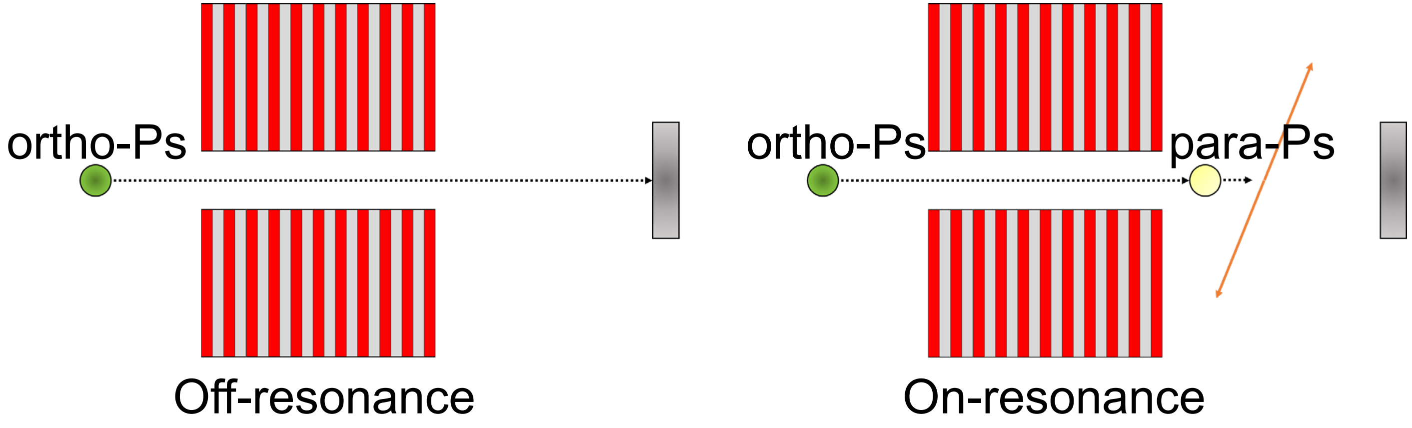


Recently direct observation of the hyperfine transition was observed.
(Yamazaki et al., PRL 108 (2012) 253401; Miyazaki et al., PTEP (2015))

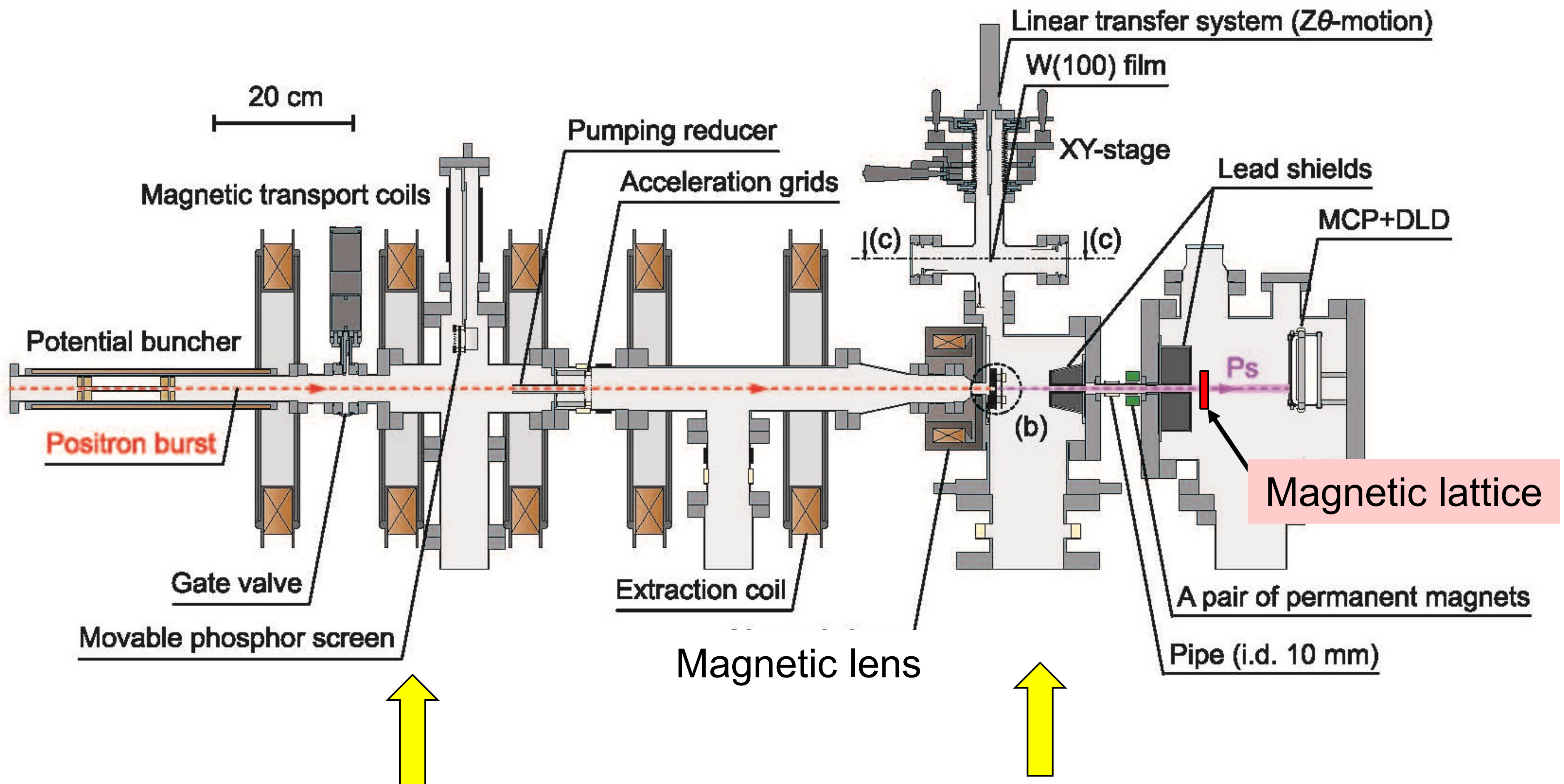
We tried to Observe the RCE for this hyperfine structure.

Observation of Resonant Coherent Excitation (RCE) of Ps





Observation of Resonant Coherent Excitation (RCE) of ortho-Ps



Ps production chamber

Pulsed positron transport line
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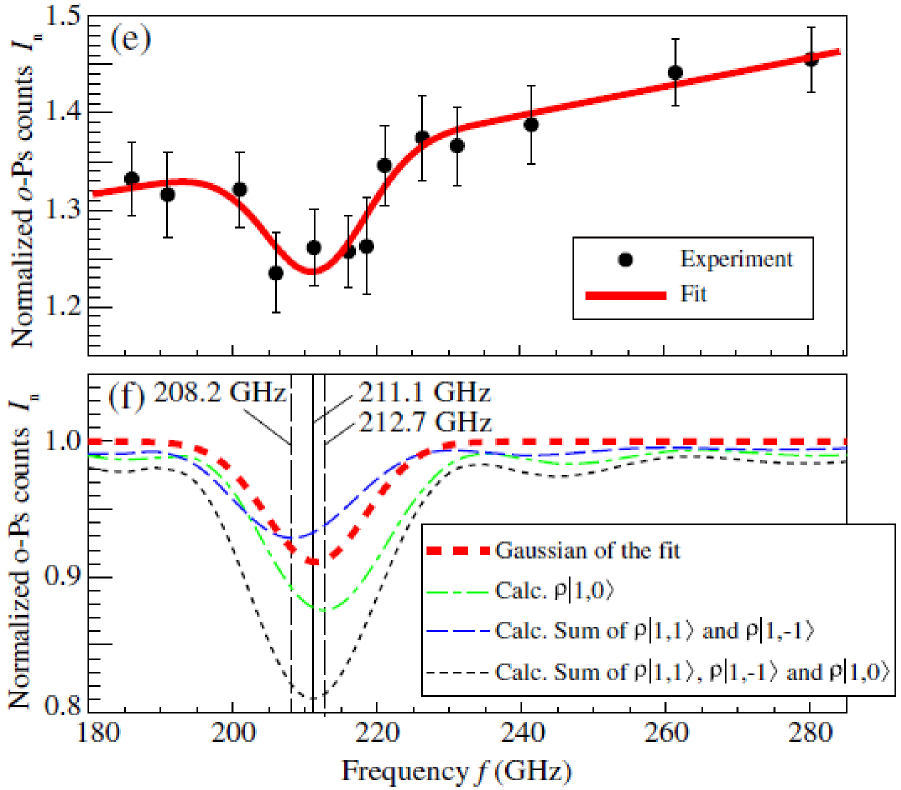
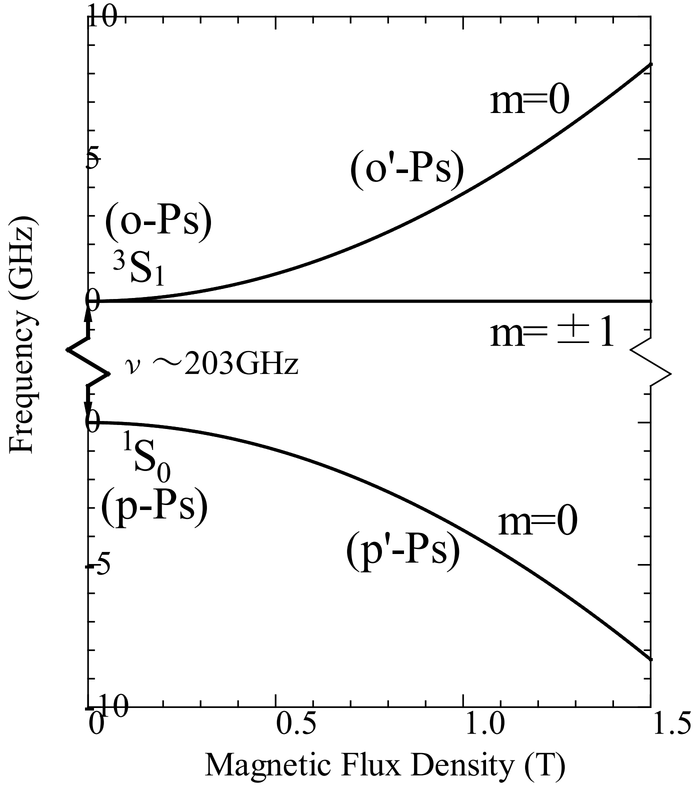
Observation of Resonant Coherent Excitation (RCE) of ortho-Ps





A dip due to the hyperfine transition was observed.
This is the first step to measure energy intervals of Ps using RCE.

Nagata, Michishio, Iizuka, Kikutani, Chiari, Tanaka, Nagashima, PRL 124, 173202 (2020)

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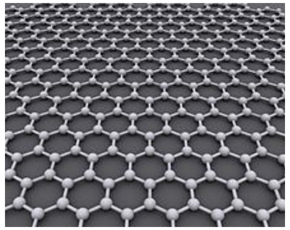
- Observation of resonant coherent excitation of Ps through a static periodic magnetic field
- Measurement of Ps transmittance through graphene
- Observation of quantum interference of Ps
- Future experiments

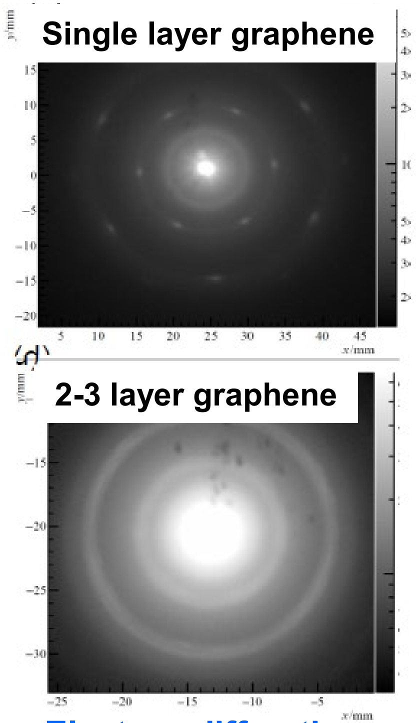
Observation of Ps passing through graphene

Ps passing through a free-standing graphene thin film was observed.

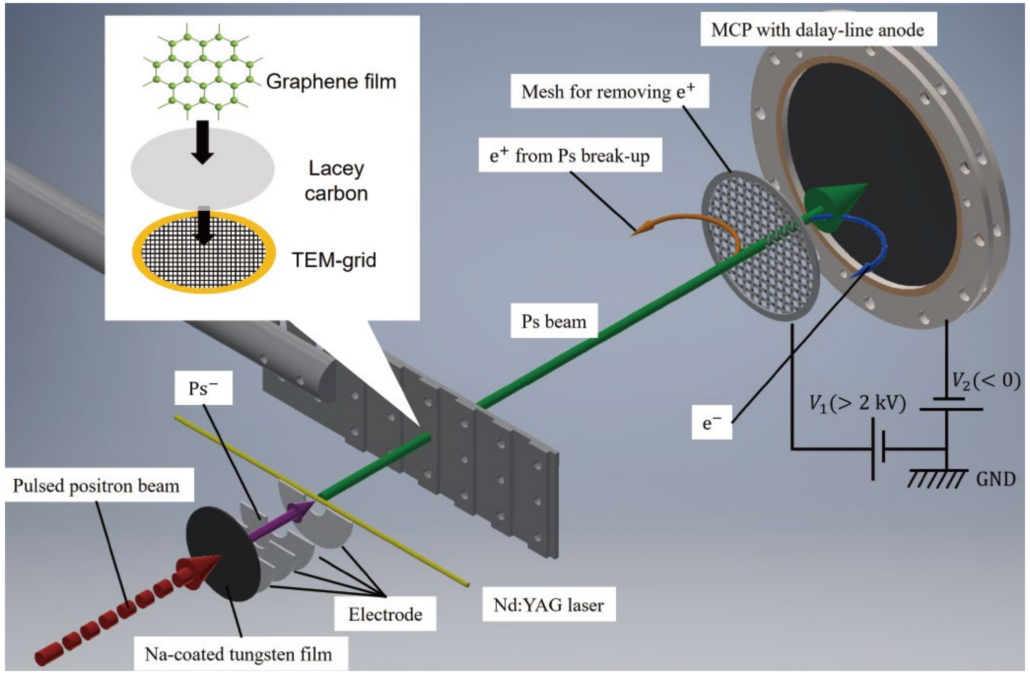


Used sample: free-standing graphene thin film on lacey carbon,
or Cu TEM grid

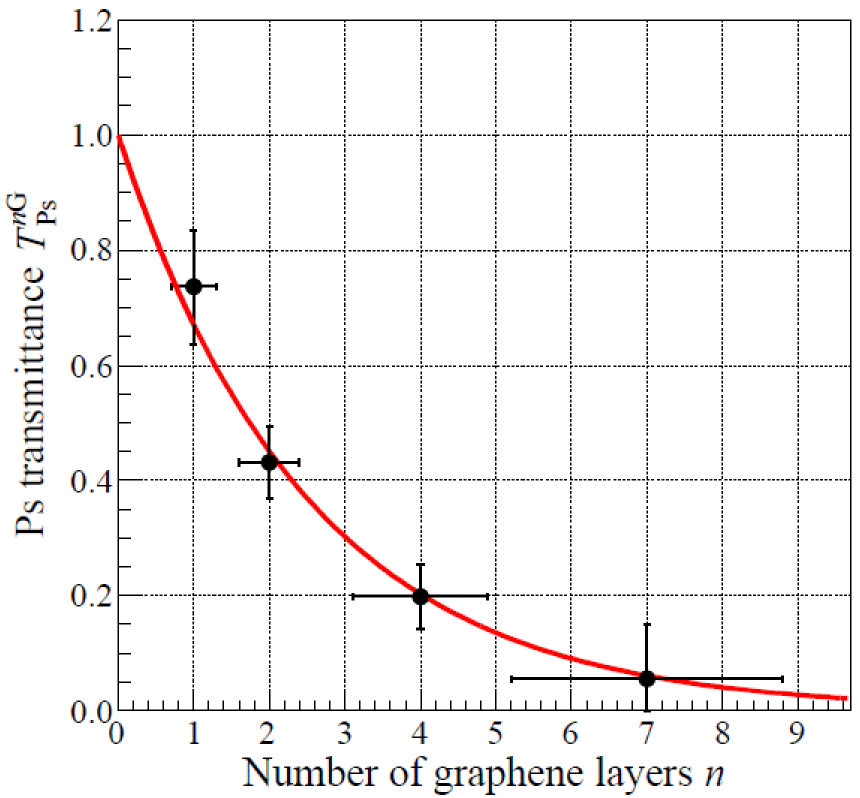
Diameter: 1.5 mm



Electron diffraction.



Observation of Ps passing through graphene



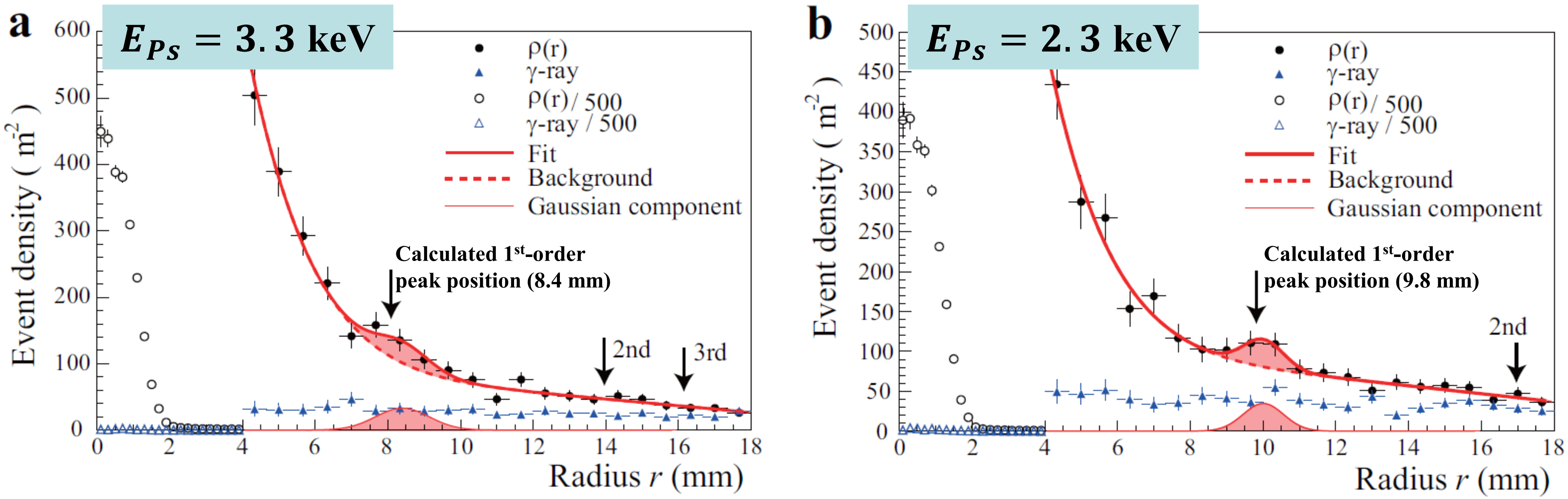
Ps transmittance plotted against the number of graphene layers.

E_{Ps}= 3.3 keV

These results provide the most basic data for considering how Ps atoms penetrate solids.

R. Mikami et al., J. Phys. Conf. Ser. 3029, 012008 (2025).

Diffraction of positronium through graphene 2-3 layer film, @ 3.3 keV and 2.3 keV



At both 3.3 keV and 2.3 keV,

a bump can be seen at the calculated 1st-order peak position.

Quantum interference of Ps beam was observed

in the year marking the 100th anniversary

of the establishment of quantum mechanics.

Y. Nagata, R. Mikami, Z. Zafar, and Y. Nagashima, Nat. Commun. 17, 1159 (2026).
(Published on 23 Dec. 2025)

Outline of this talk

- What is Ps^-?
- Efficient formation of Ps^- using alkali-metal coated surface
- An energy-tunable Ps beams produce using photodetachment of Ps^-
- Observation of resonant coherent excitation of Ps through a static periodic magnetic field
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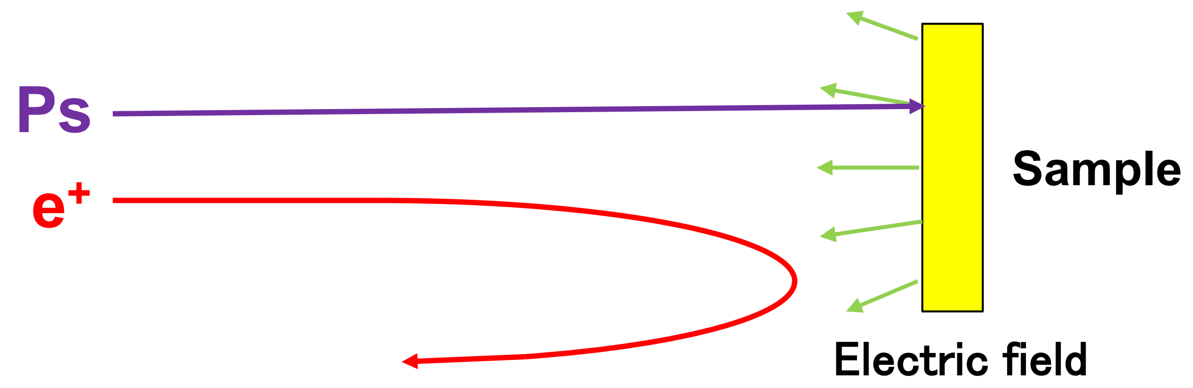
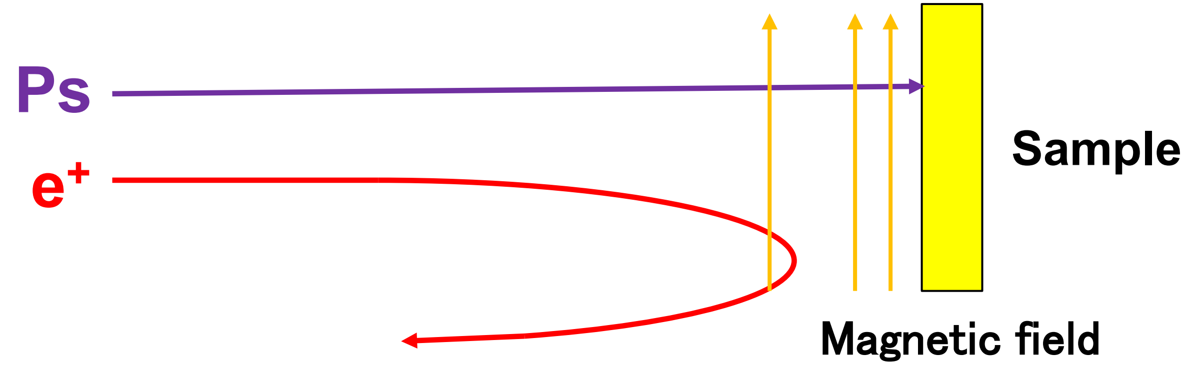
- Observation of quantum interference of Ps
- Future experiments

Future experiments

- Investigation of solid surfaces using Ps beam
- Observation of the effect of gravity on Ps

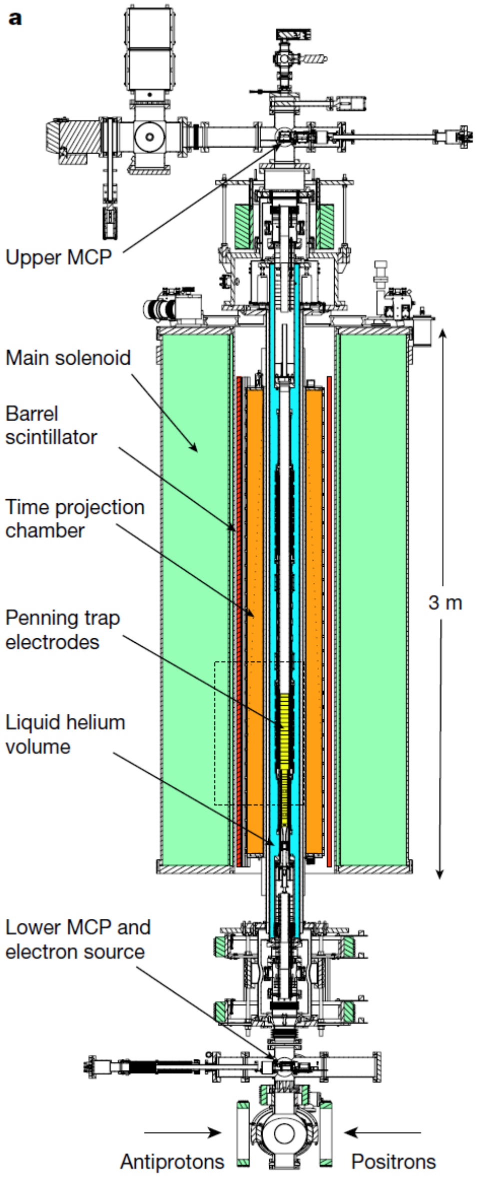
Depth profile measurements for samples generating electric or magnetic fields





The trajectories of slow e^+ are affected by the electric or magnetic fields from the sample.
In case of Ps, its trajectory and energy are not affected by the fields.
This enables measurements to be performed with the correct injection energy.

Measurement of gravitation force on anti-hydrogen



Repulsive "antigravity" is ruled out!

No gravitational measurements have been made on leptons, not even on electrons.

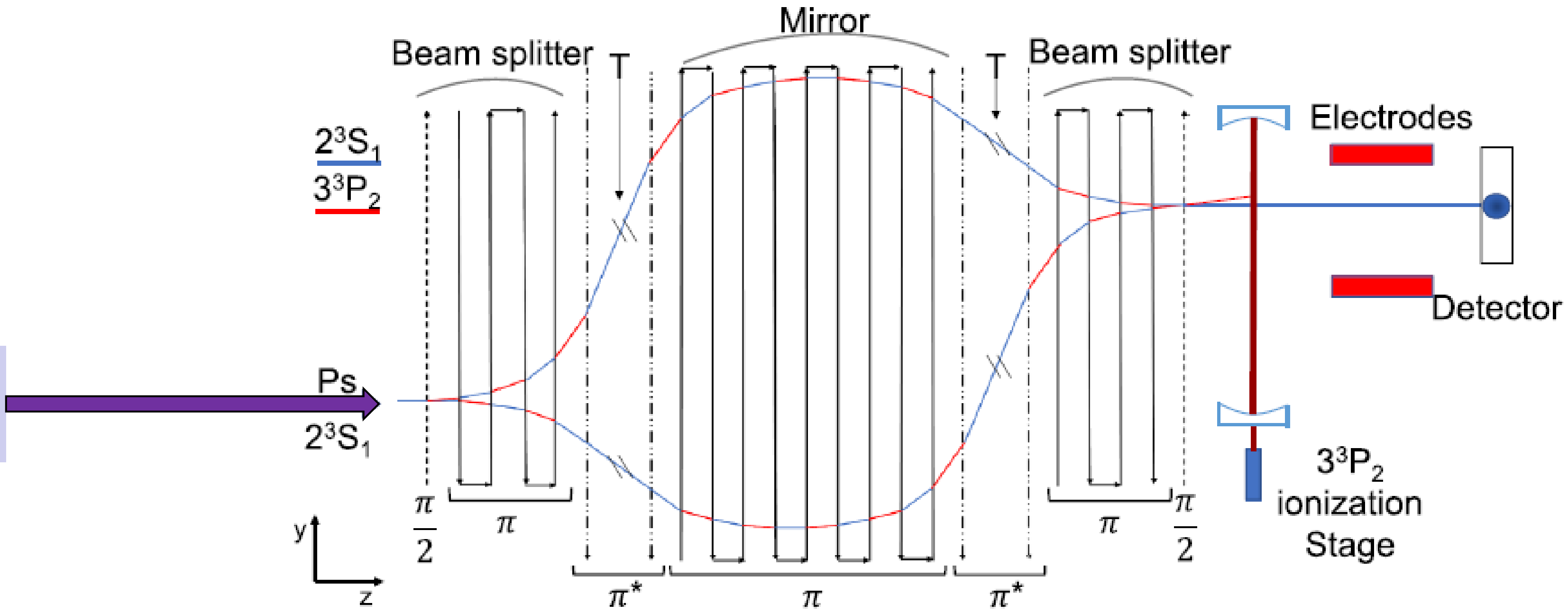
This is because gravitational force from earth
is extremely weak compared with residual electric fields.
One way to solve this is to measure the gravity of Ps.

The Ps beam we have developed could be used for this purpose In future.

E. K. Anderson (ALPHA-g experiment at CERN), Nature 621, 716 (2023)

Measurement of gravitation force on Ps atoms

Ps beam produced via photodetachment of Ps^-



Ps Mach–Zehnder interferometer
utilising large-area light-pulse atom interferometry techniques

G. Vinelli et al., Class. Quantum Grav. 40, 205024 (2023)

This will require a Ps beam with much higher intensity than currently available.
It will be a challenging experiment

Future experiments

- Ps beam manipulation using surfaces
- Observation of the effect of gravity on Ps

I believe there are numerous research projects that can be undertaken using the Ps beam which we have developed from the perspectives of atomic nuclei and elementary particles.

Future experiments

- Ps beam manipulation using surfaces
- Observation of the effect of gravity on Ps

**Facilities capable of generating high-intensity,
slow positron beams are essential for future positron research.
Both high-intensity facilities capable of producing over 10^9 e^+/s
and those capable of producing around 10^7 e^+/s play a significant role.
I hope that such a facility will be realized at JLab at the earliest opportunity.**

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Matsuo Zaidan