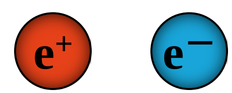
高強度陽電子源の利用
－ポジトロニウムビーム生成とその応用－

Use of the intense positron source
－Production of an energy tunable positronium beam and its applications－



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陽電子の基本的性質：

◆陽電子は電子と出会うと対消滅することがある。

◆消滅率： $\lambda = \pi r_0^2\, c\, n$

r_0 ：電子の古典半径
c ：光速
n ：電子密度

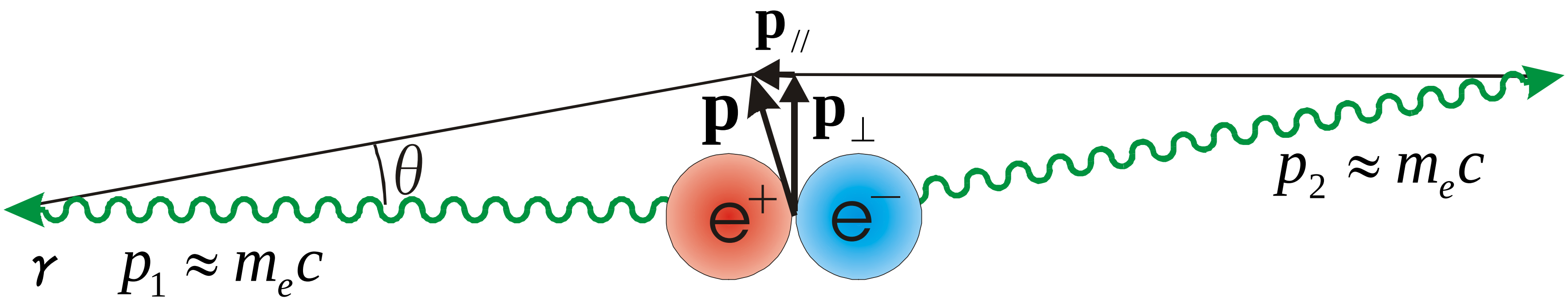
$r_0 = 2.818 \times 10^{-15}$ m ＜＜ a_0 (Bohr 半径、0.53Å）

陽電子の消滅断面積 ＜＜ 散乱断面積

陽電子は物質中でも、なかなか対消滅しない！

陽電子を物質に入射すると、消滅前に熱化する。

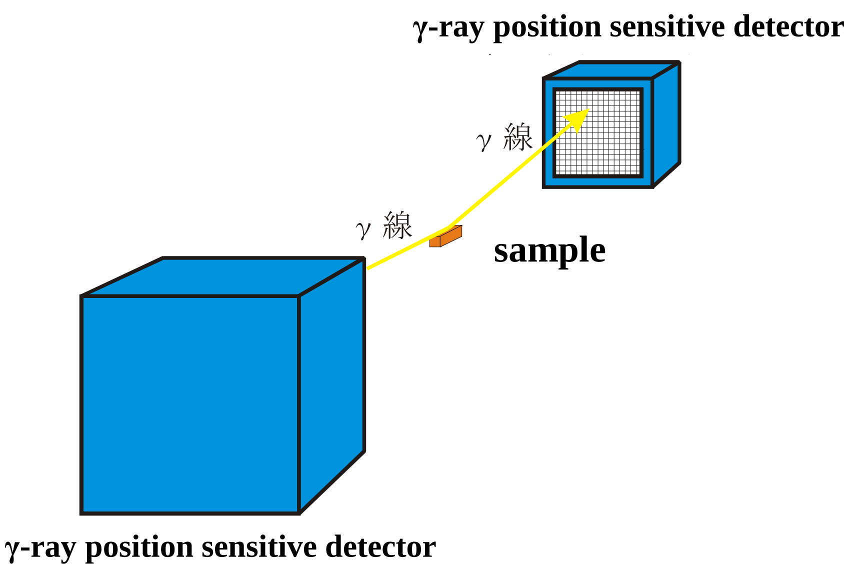
Angular correlation of annihilation radiation (ACAR, 2光子角相関法)



The positrons in solids are thermalized within a few ps.

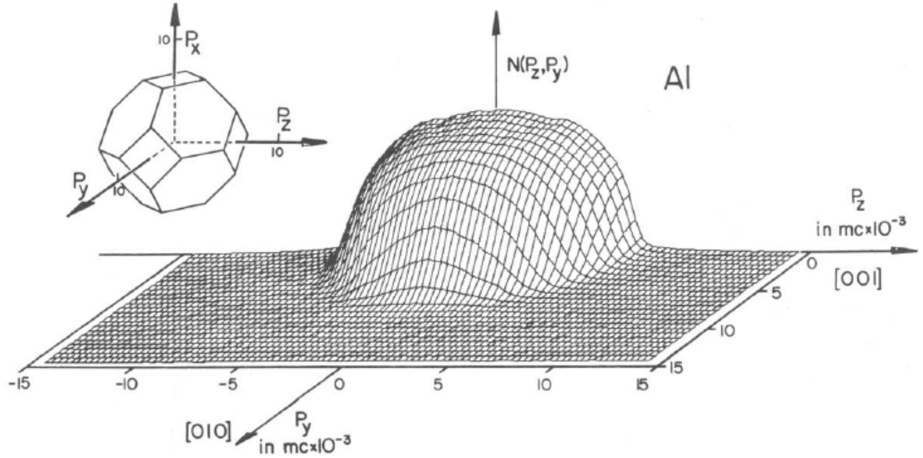
$$\theta < 1^\circ$$

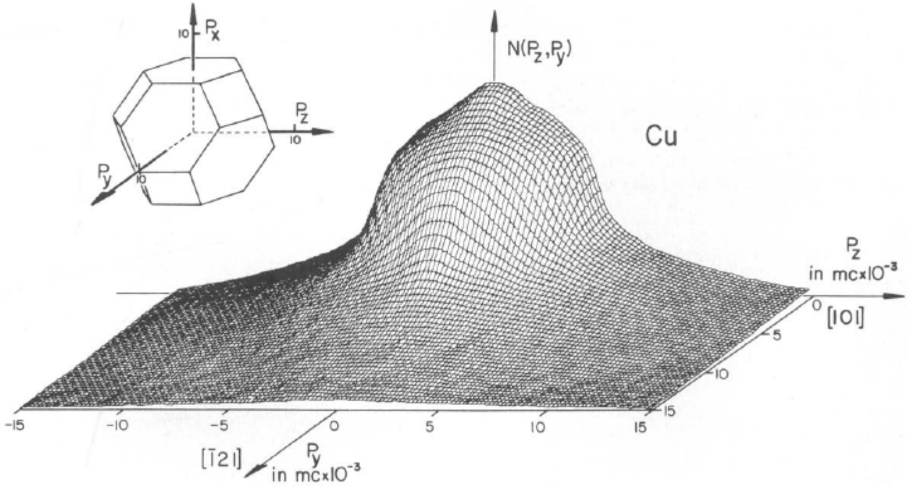
$$p_\perp = \cos\theta \approx m_e c\theta \qquad E_1 = m_e c^2 + \frac{p_{//} c}{2}$$



2D ACAR apparatus

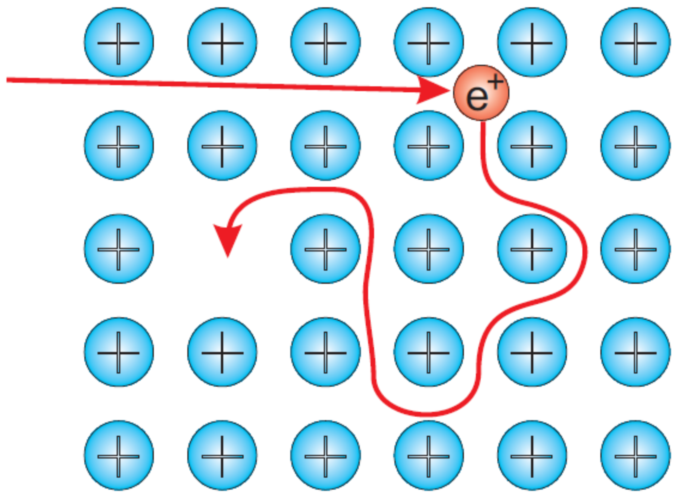
SSD (Germanium detector)



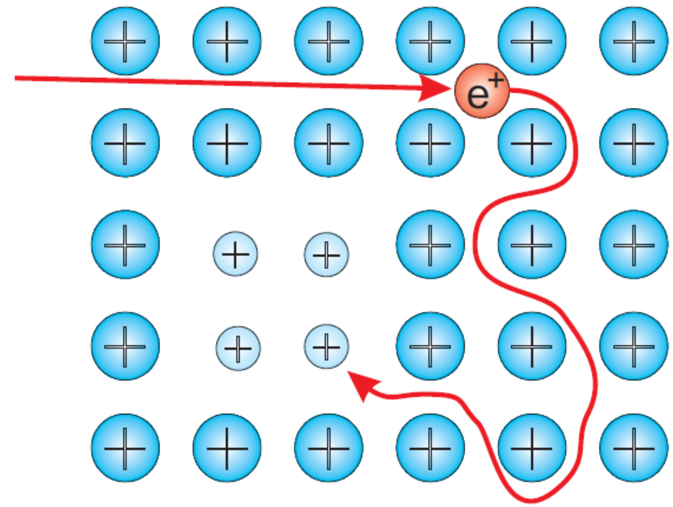


(Berko, Haghgooie and Mader, Phys. Lett. A 63 (1977) 335)

ACAR data for Al and Cu



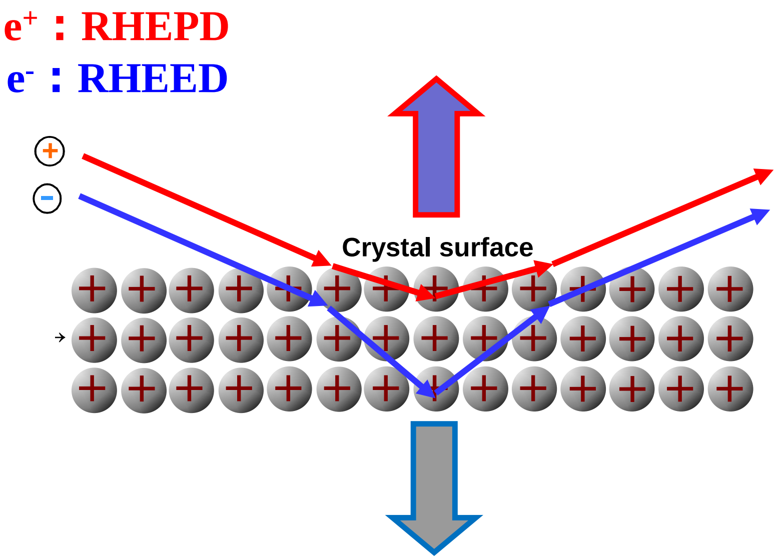
Positrons are trapped
at vacancy type defects

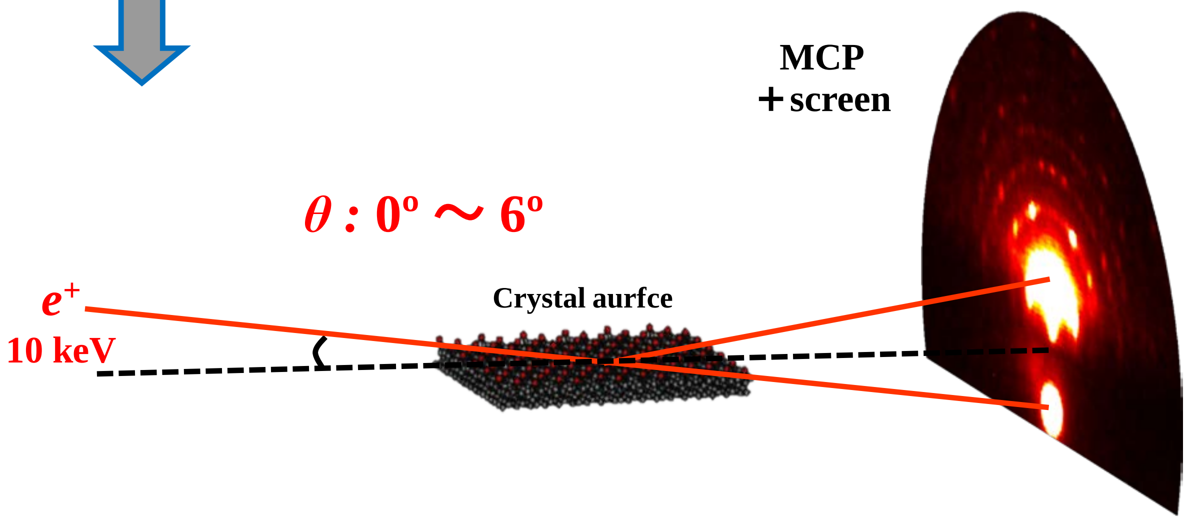


Positrons are trapped
at impurity precipitates with lower potentials

Defects can be studied using positrons.

When positrons impinge on crystal surfaces with glancing angles,…



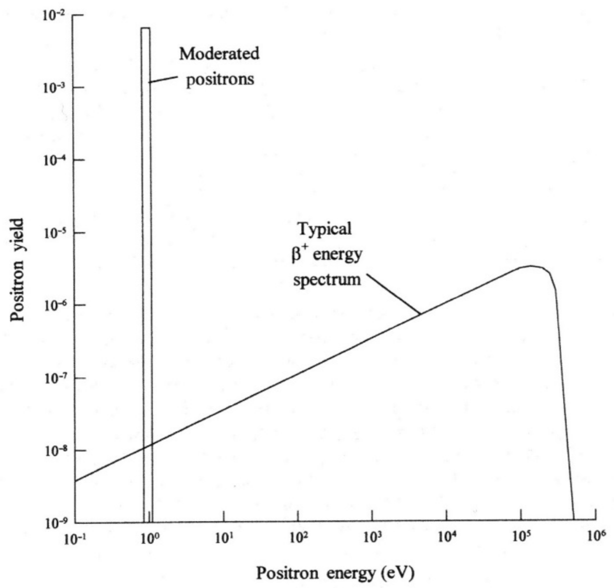


Information on the top most surface structures can be obtained.

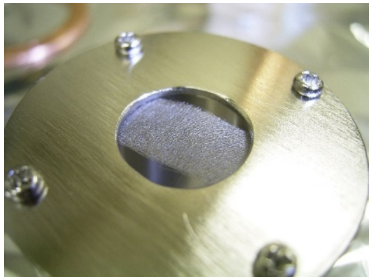
(In the case of RHEED, the effects on the bulk structure are admixed.)

Kawasuso et al., Phys. Rev. Lett. 81 (1998) 2695

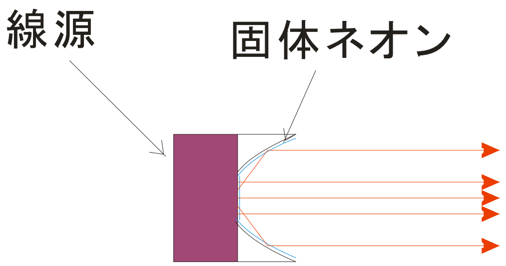
Positrons generated in β^+decay have wide energy distribution.



Positron source capsule



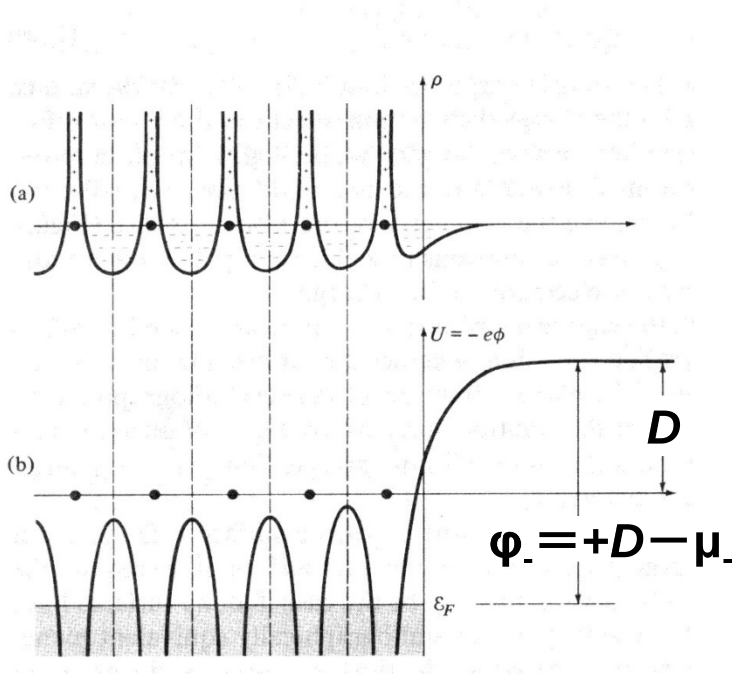
Tungsten mesh



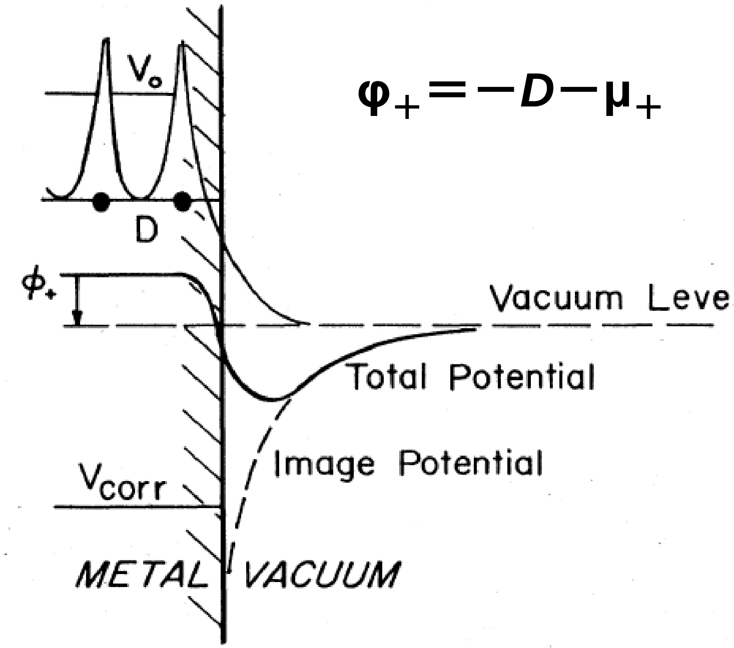
Solid neon

Positron moderation efficiencies: 5×10^{-4} (tungsten mesh), 5×10^{-3} (solid neon)

Slow positron beam intensities:
740MBq $\times 0.9 \times (5\times10^{-4}) = 3\times10^{5}$ e^+/s (tungsten moderator)
740MBq $\times 0.9 \times (5\times10^{-3}) = 3\times10^{6}$ e^+/s (solid neon moderator)



(Ashcroft and Mermin)



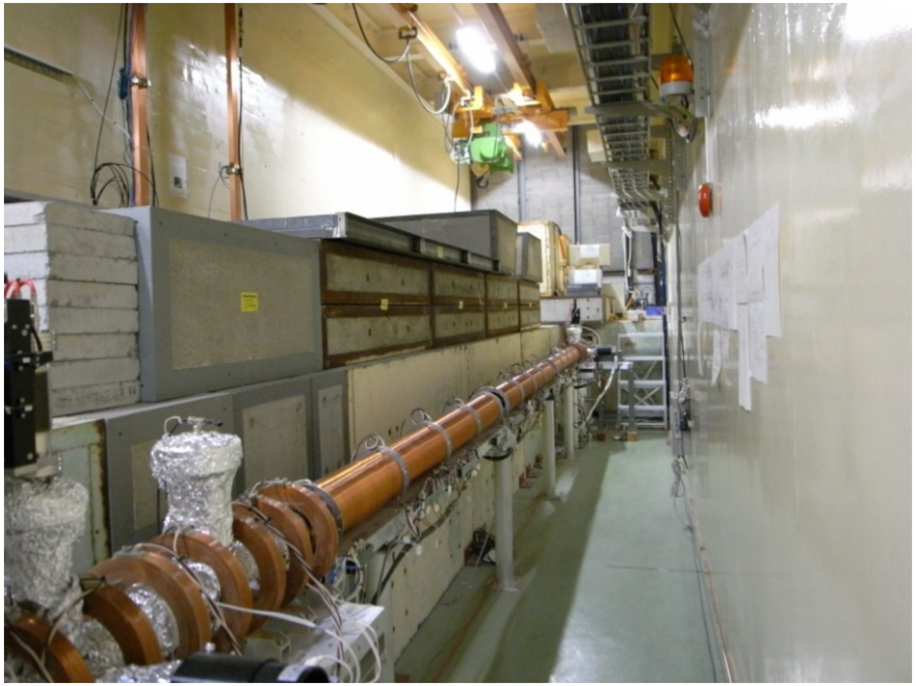
(Schultz and Lynn, Rev. Mod. Phys. 60 (1988) 701)

電子の仕事関数: $\phi_{-} = +D - \mu_{-}$

陽電子の仕事関数: $\phi_{+} = -D - \mu_{+}$

金属表面近傍における電子および陽電子のエネルギー準位

Intensity of present slow positron beams at KEK:



Positron soruce : Pair production of Bremsstrahlung X-rays from linac

Linac power : 600W

Energy : 55MeV

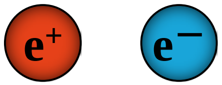
Moderated using tungsten vanes

Positron flux : 5×10^{7} e^{+}/s

Vacuum : 2×10^{-8} Pa

Pulsed beam, width ～ 10ns

positronium (Ps)

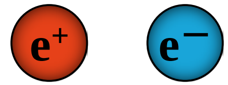


- ✓ Hydrogen-like bound state
- ✓ Lightest neutral atom
- ✓ Neutralized electron
- ✓ Neutralized positron
- ✓ Binding energy = 6.80eV
- ✓ mean distance $e^+ - e^-$ = $3a_0$
- ✓ Two spin states:

  Ortho-Ps (S=1, triplet)： lifetime=142ns, Self-annihilates into 3 γ

  Para-Ps (S=0, singlet)： lifetime=125ps, Self-annihilates into 2γ
- ✓ Many excited states

positronium (Ps)

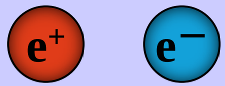


Recently, we have developed an energy tunable Ps beam.

This technique has opened the door to a new era of experimental investigations on surfaces, atoms and molecules.

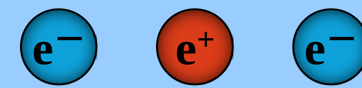
Background: A technique to produce positronium negative ions (Ps^-) efficiently has been developed.

positronium (Ps)



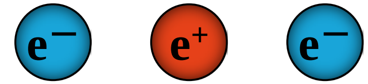
- ✓ H atom like state
- ✓ Lightest “atom”
- ✓ Binding energy : 6.80eV
- ✓ Mean distance $e^+ - e^-$: $3a_0$
- ✓ Two eigenstates (ground states)
  - Ortho-Ps (S=1, triplet)
    - Lifetime in vacuum : 142ns
    - Self-annihilates into 3γ .
  - Para-Ps (S=0, singlet)
    - Lifetime in vacuum : 125ps
  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

positronium negative ion (Ps^-)

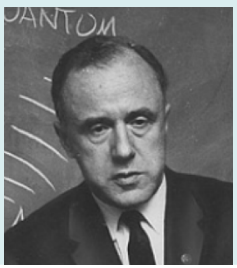


- ✓ H^- ion like state
- ✓ Simplest three body system
- ✓ e^- binding energy to Ps : 0.33eV
  The energy required to break up into 3 isolated particles : 7.13eV
- ✓ Mean distance $e^+ - e^-$: $5.5a_0$
- ✓ Only one state
  - Lifetime in vacuum : 479ps
  - Self-annihilates into 2γ.

Discovery of the Ps^-

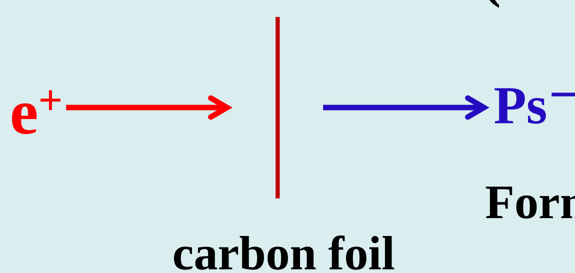


"The tri-electron system has a radioactive mean lifetime of the order of 10^{-10} sec, and is calculated to be stable by at least 0.19eV against dissociation into a bi-electron and a free electron or positron."
"For the formation of an entity of the type P^{+--}, the most reasonable mechanism appears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



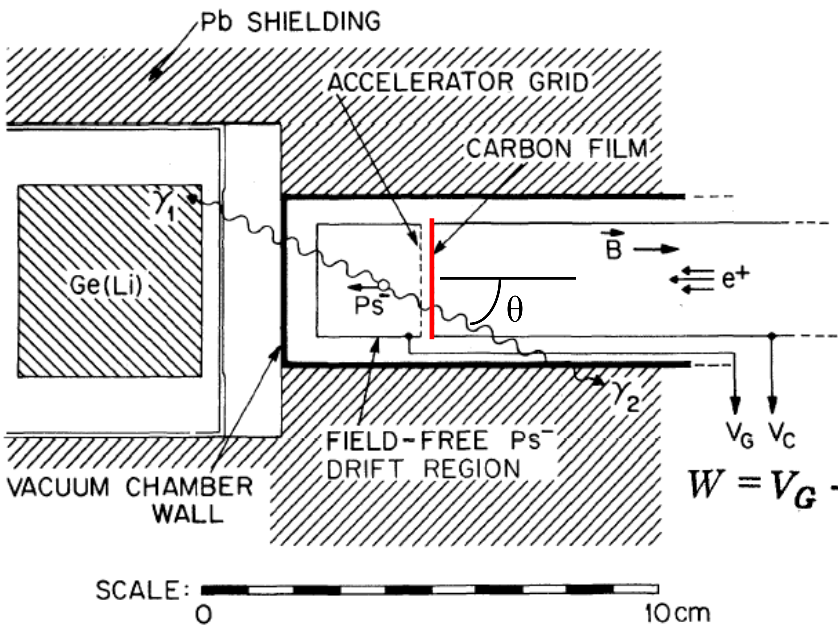
(Wheeler, Ann. New York Acad. of Sci. 3 (1946) 219)

First observation : performed by Allen Mills, Jr. in 1981.
(Mills, PRL 46 (1981) 717)



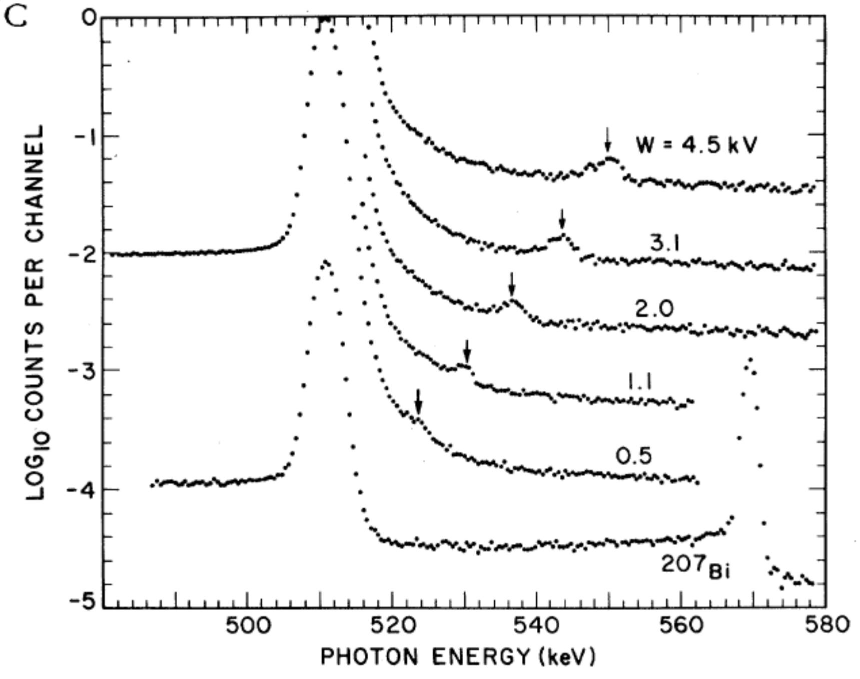
Formation efficiency ~ 0.028%

First observation of Ps⁻ (Mills, 1981)



$W = V_G - V_C$

- **Slow positrons (470 eV) were guided to a thin carbon target.**
- **Ps⁻ formed were accelerated by the electric field and detected by their Doppler-shifted annihilation lines.**

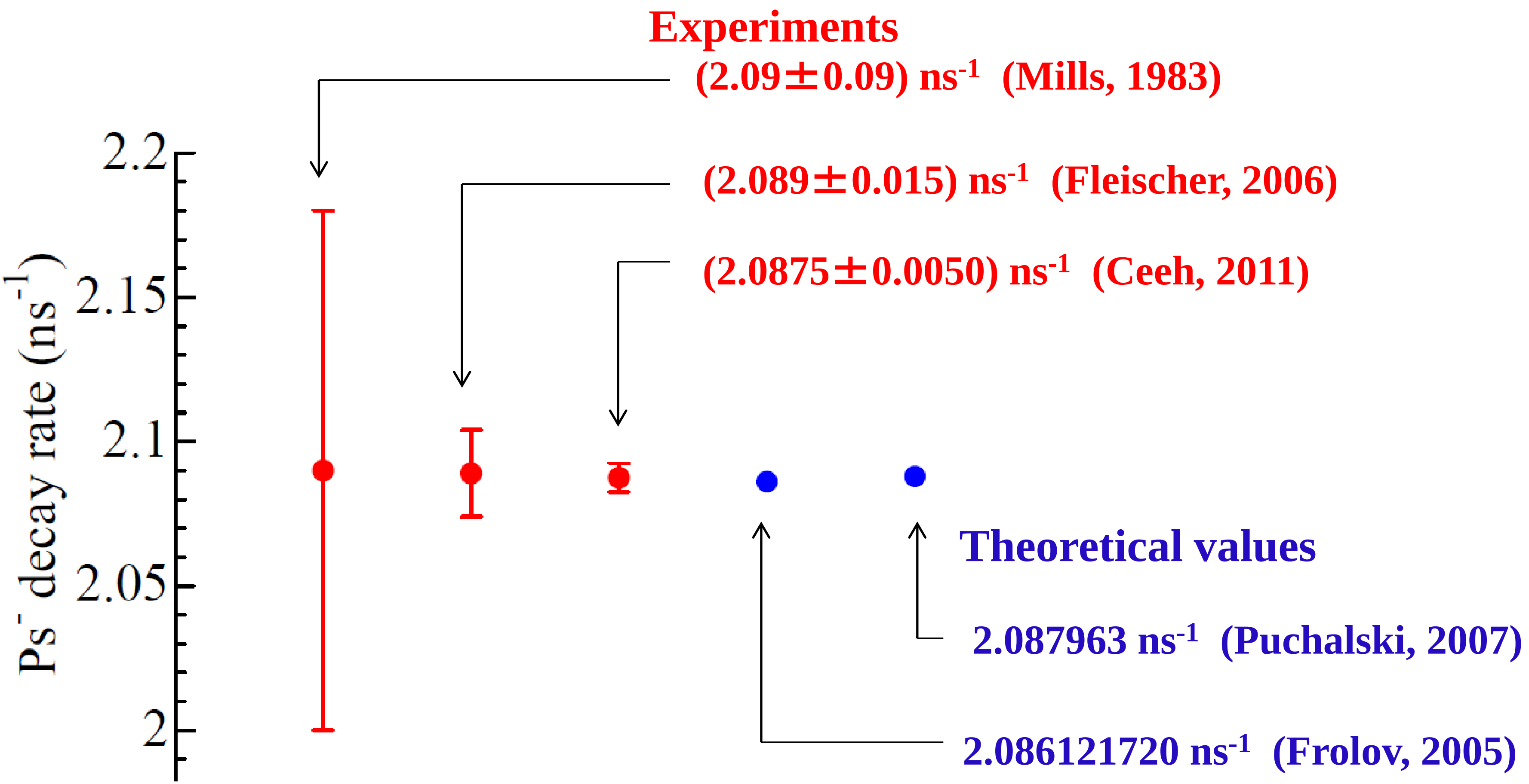


Ps⁻ formation was confirmed.

Ps⁻ emission efficiency = 0.028%

(Mills, PRL 46 (1981) 717)

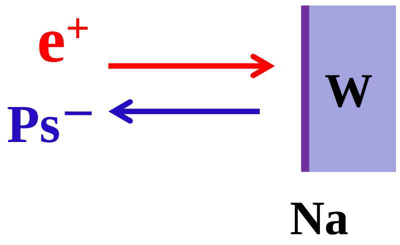
Measurements of Ps^- decay rate – comparison with theoretical values



All experimental results are consistent with recent theoretical values.

Ps^- production using alkali metal coated tungsten surfaces (2006 – present)

Ps^- production using Na coated tungsten surfaces



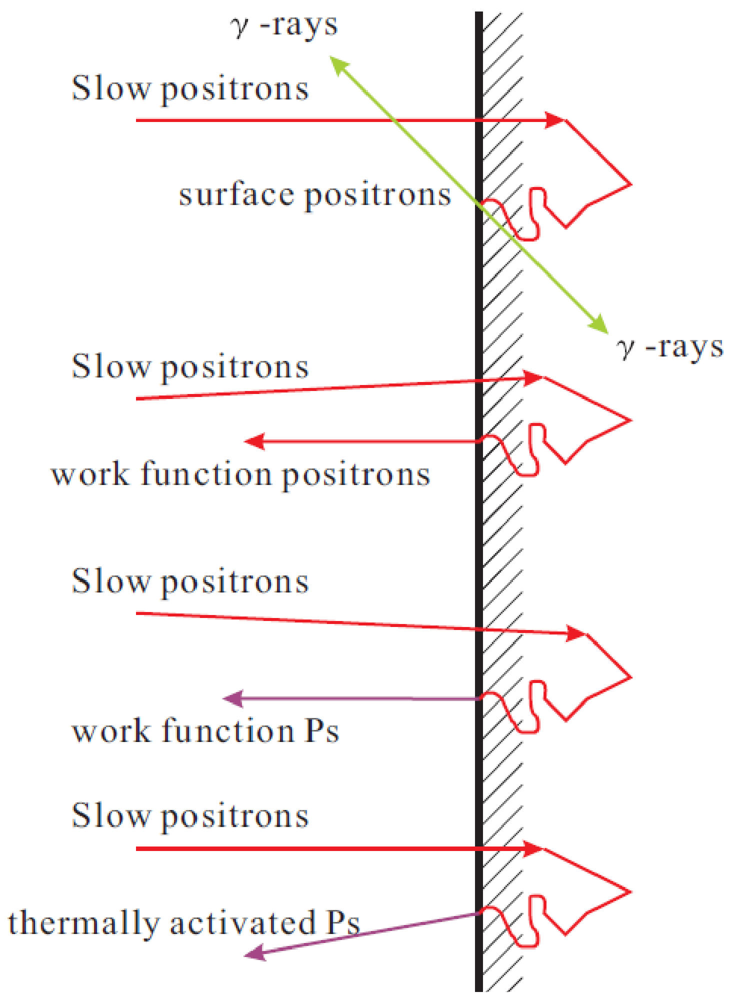
efficiency

~ 2%

- ✓ **Observation of Ps^- photodetachment**
- ✓ **Observation of Ps^- resonant photodetachment**
- ✓ **Production of energy tunable Ps beams**

Nagashima et al., NJP 10 (2008) 123029
Terabe et al., NJP 14 (2012) 015003
Nagashima, Phys. Rep. 545 (2014) 95

Positrons at surfaces



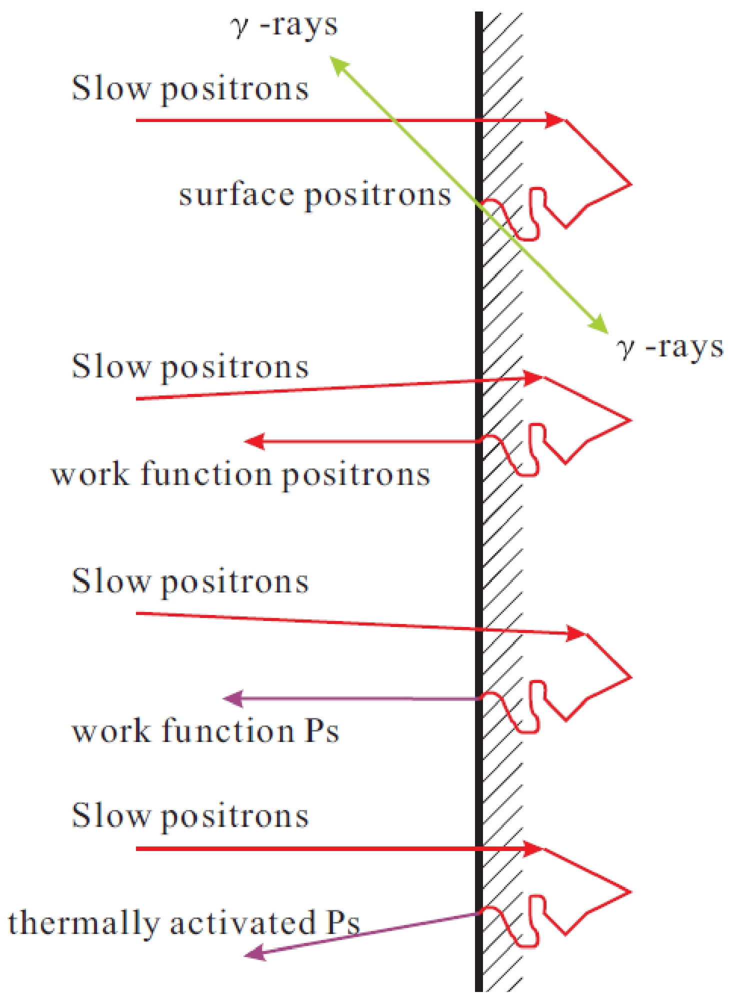
ϕ_+ : **e⁺ work function**

(The energy required to emit e⁺)

$$\phi_+ < 0$$

e⁺ are emitted from the surface.

Positrons at surfaces



The energy required to emit Ps (Ps affinity) :

$$\phi_{\mathrm{Ps}} = \phi_{+} + \phi_{-} - 6.80\,\mathrm{eV}$$

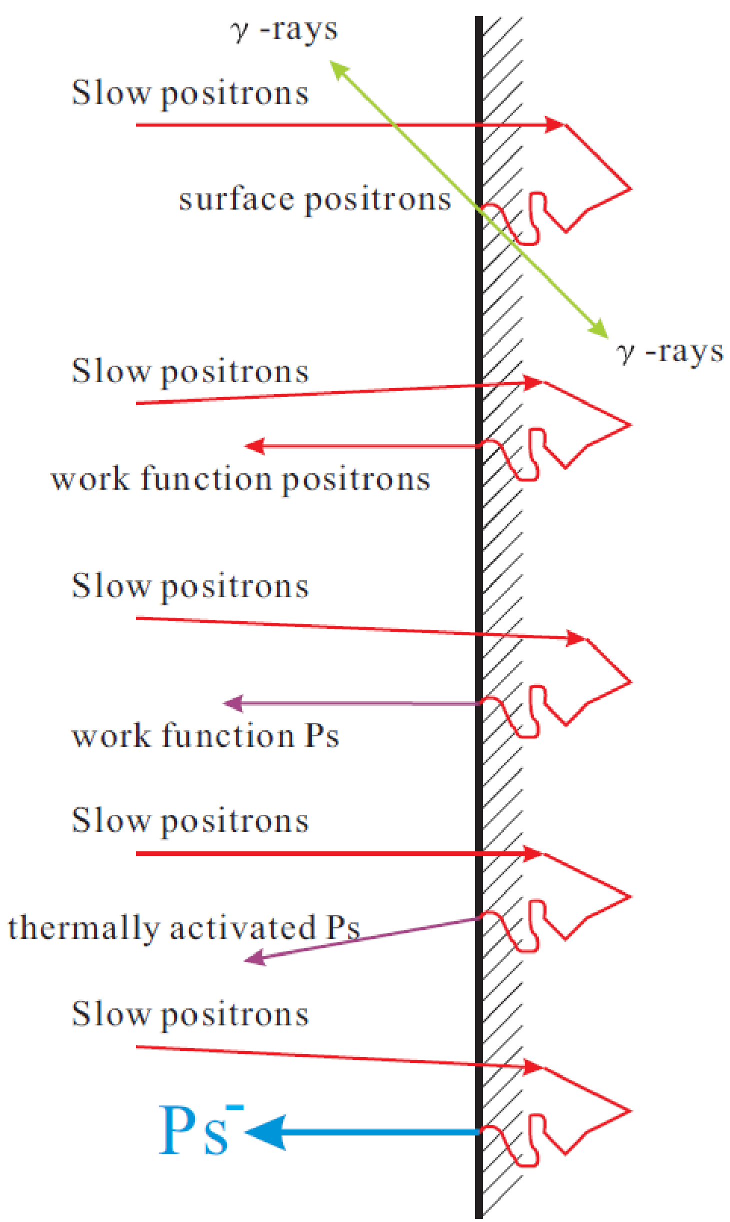
ϕ_{+} : **e^{+} work function**

ϕ_{-} : **e^{-} work function**

$$\phi_{Ps} < 0$$

Ps atoms are emitted from the surface.

Positrons at surfaces



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

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

e^+ work function

e^- work function

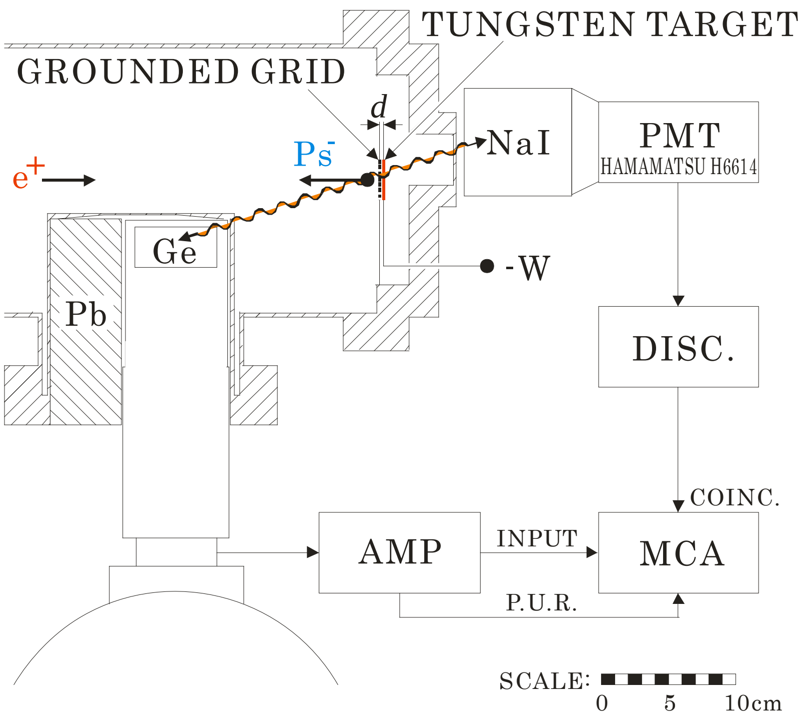
The energy required to break up Ps^- into three isolated particles =(Ps binding energy, 6.80eV) +(e^- binding energy to Ps, 0.33eV)

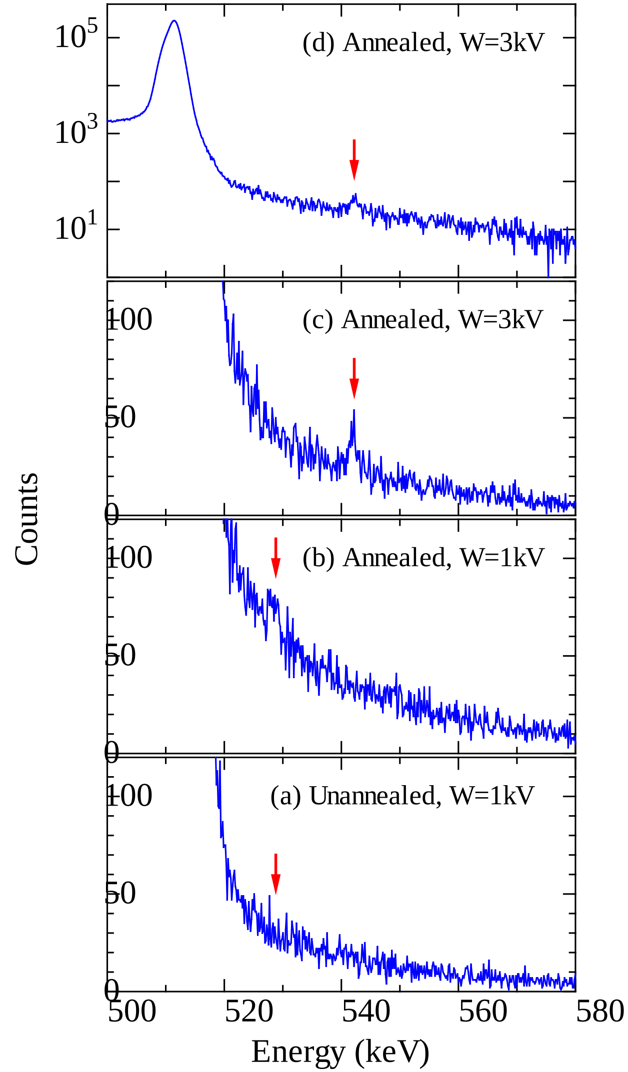
If $\phi_{Ps^-} < 0$,

Ps^- may be emitted from the surface spontaneously.

Ps⁻ emission from polycrystalline tungsten surface

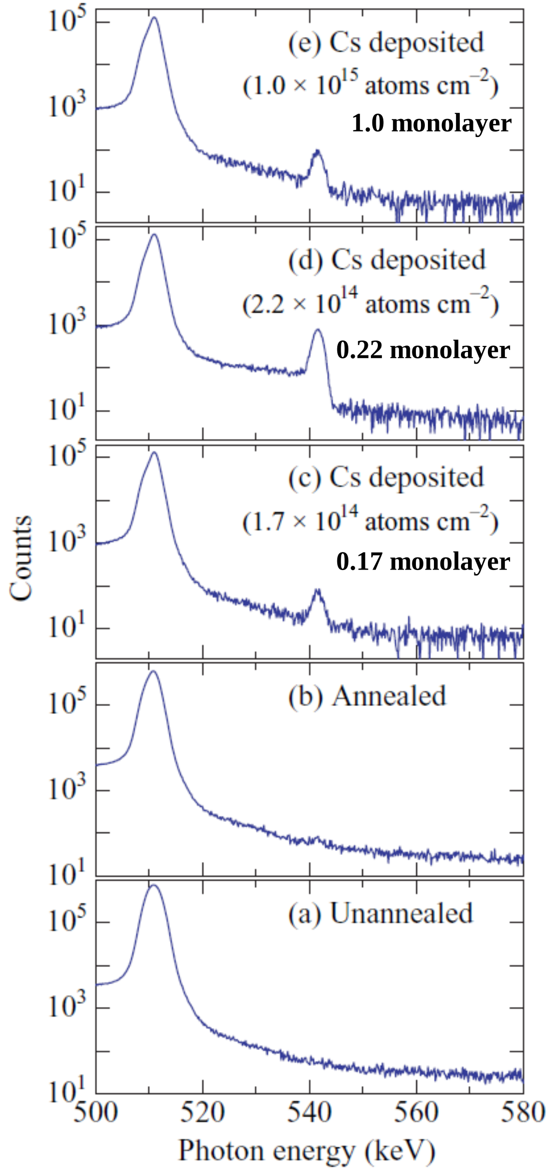
(Nagashima and Sakai, NJP 8 (2006) 319)





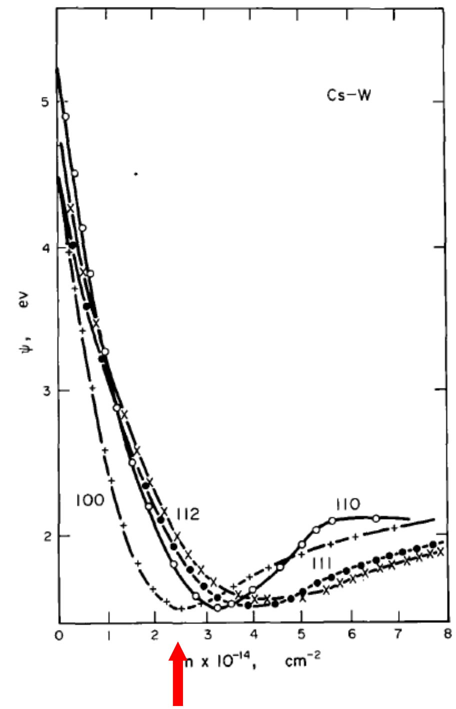
Ps⁻ emission efficiency was only 0.01% or less.

Effect of Cs coating for the Ps⁻ emission



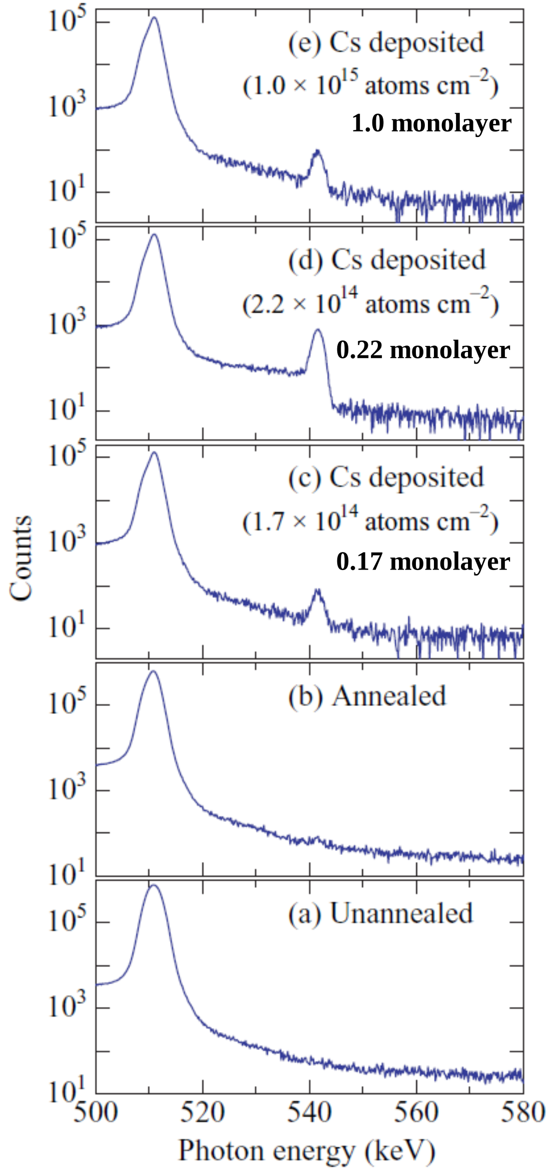
Ps⁻ intensity is the highest at 2.2×10^{14} cm^{-2} (0.22ML).

Change of ϕ_{-} for tungsten by Cs coating



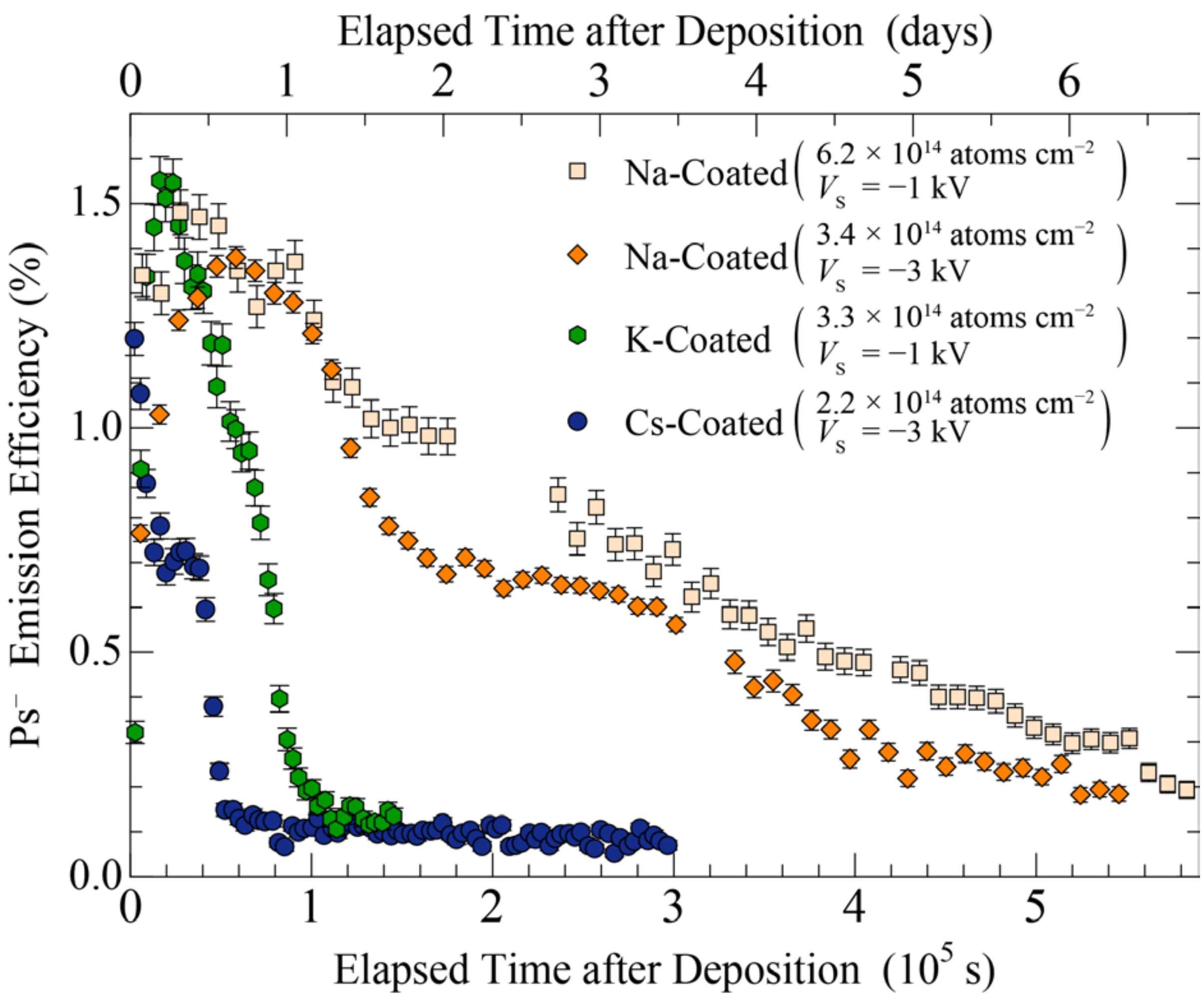
Kiejna and Wojciechowski, Prog. in Surf. Sci. 11 (1981) 293

Effect of Cs coating for the Ps^- emission



The highest efficiency was
2%,
which is *200* times higher
than that obtained for uncoated surface.

Effect of alkali metal coating for the Ps^- emission

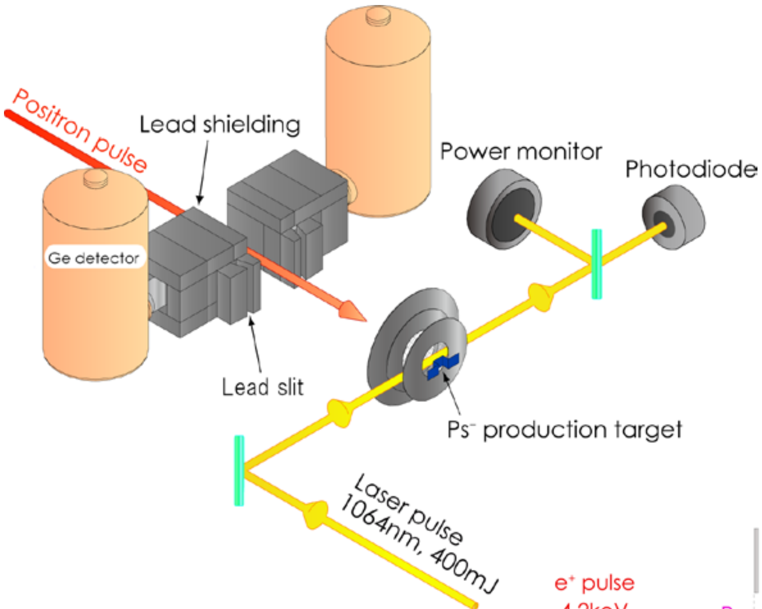


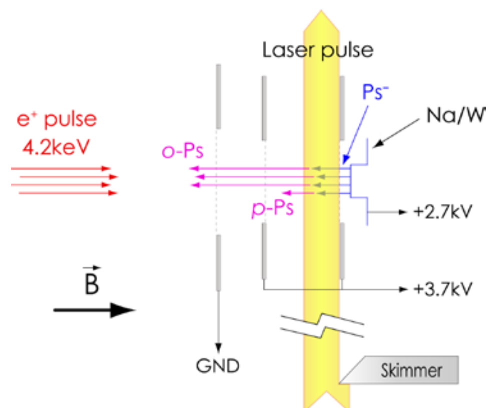
Na is the best alkali metal for the Ps^- production.

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

Ps^- photodetachment experiment

An electron linac was used to obtain a pulsed positron beam which can be synchronized with an intense pulse laser.





e^+ beam :

(from KEK Linac)

pulse width	12ns
repetition	50pps
beam intensity	4000 e^+/pulse

Laser :

Q-switched Nd: YAG

(Spectra Physics GCR290)

wave length	1064nm (1.165eV)
pulse width	12ns
repetition	25pps
power	10W

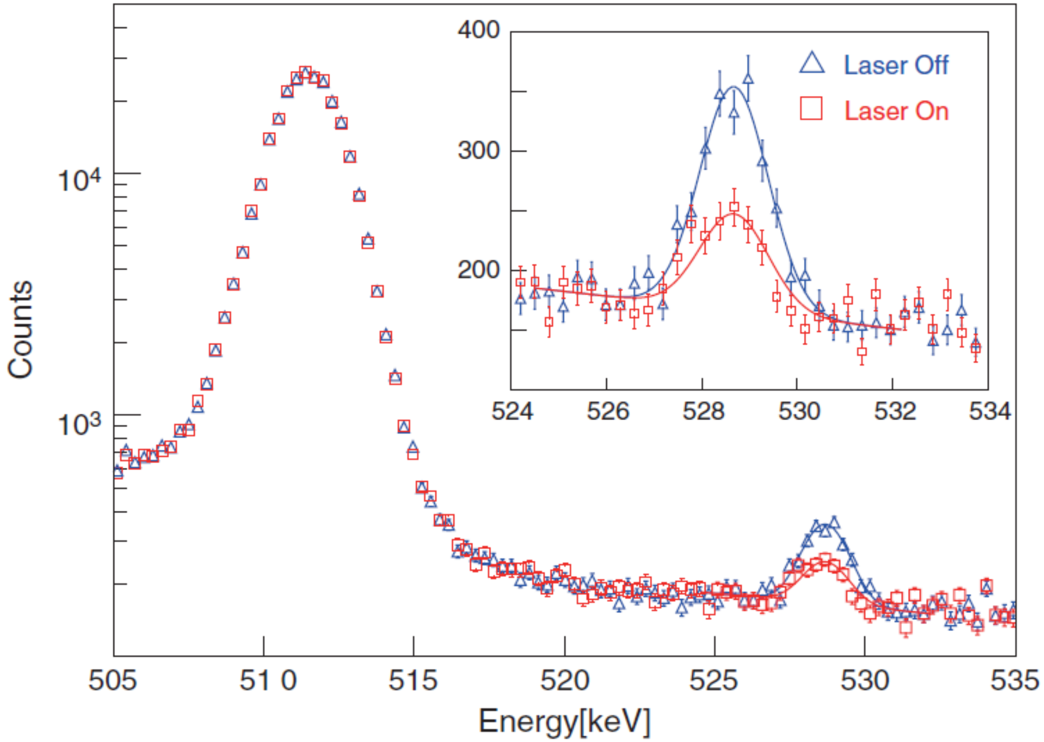
(Michishio et al., PRL 106 (2011) 153401)

Ps⁻ photodetachment experiment

Ps⁻ → 75% **o-Ps, annihilates into 3γ.**

Ps⁻ → 25% **p-Ps, annihilates into 2γ.**

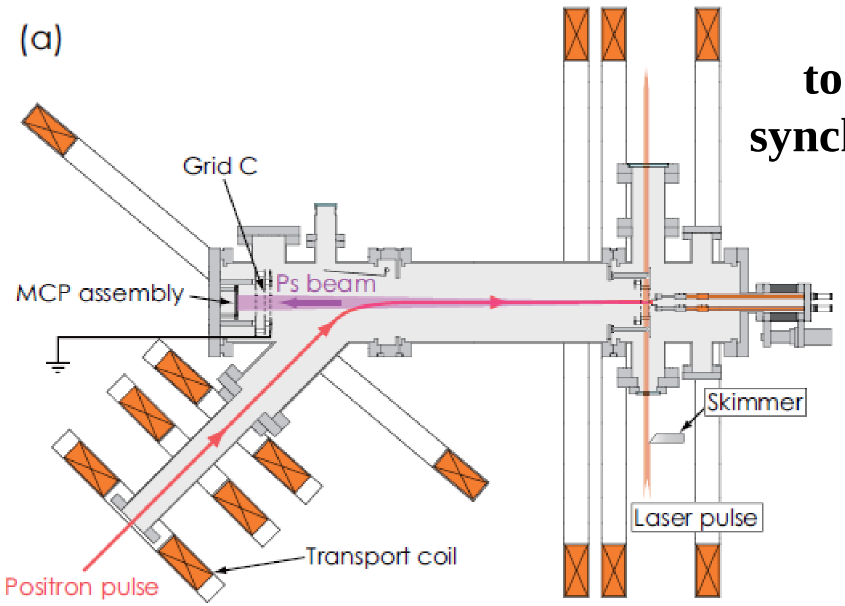
If Ps⁻ ions are photodetached, the peak intensity will decrease.



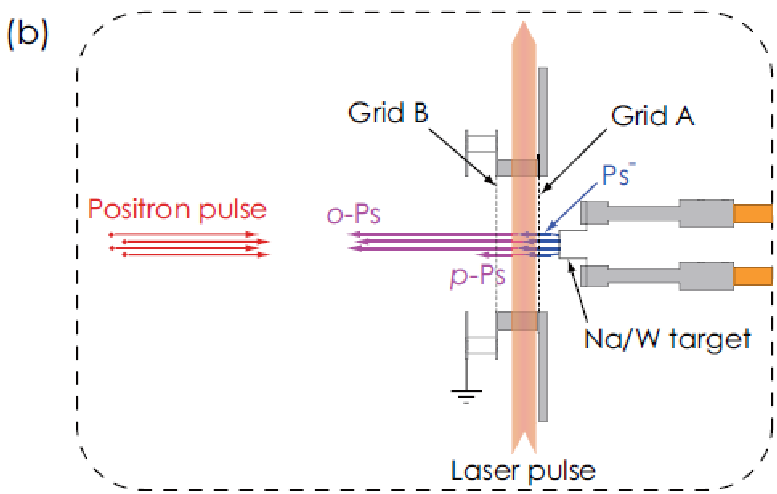
Ps⁻ photodetachment has been observed for the first time!

(Michishio et al., PRL 106 (2011) 153401)

Observation of Ps produced via Ps⁻ photodetachment



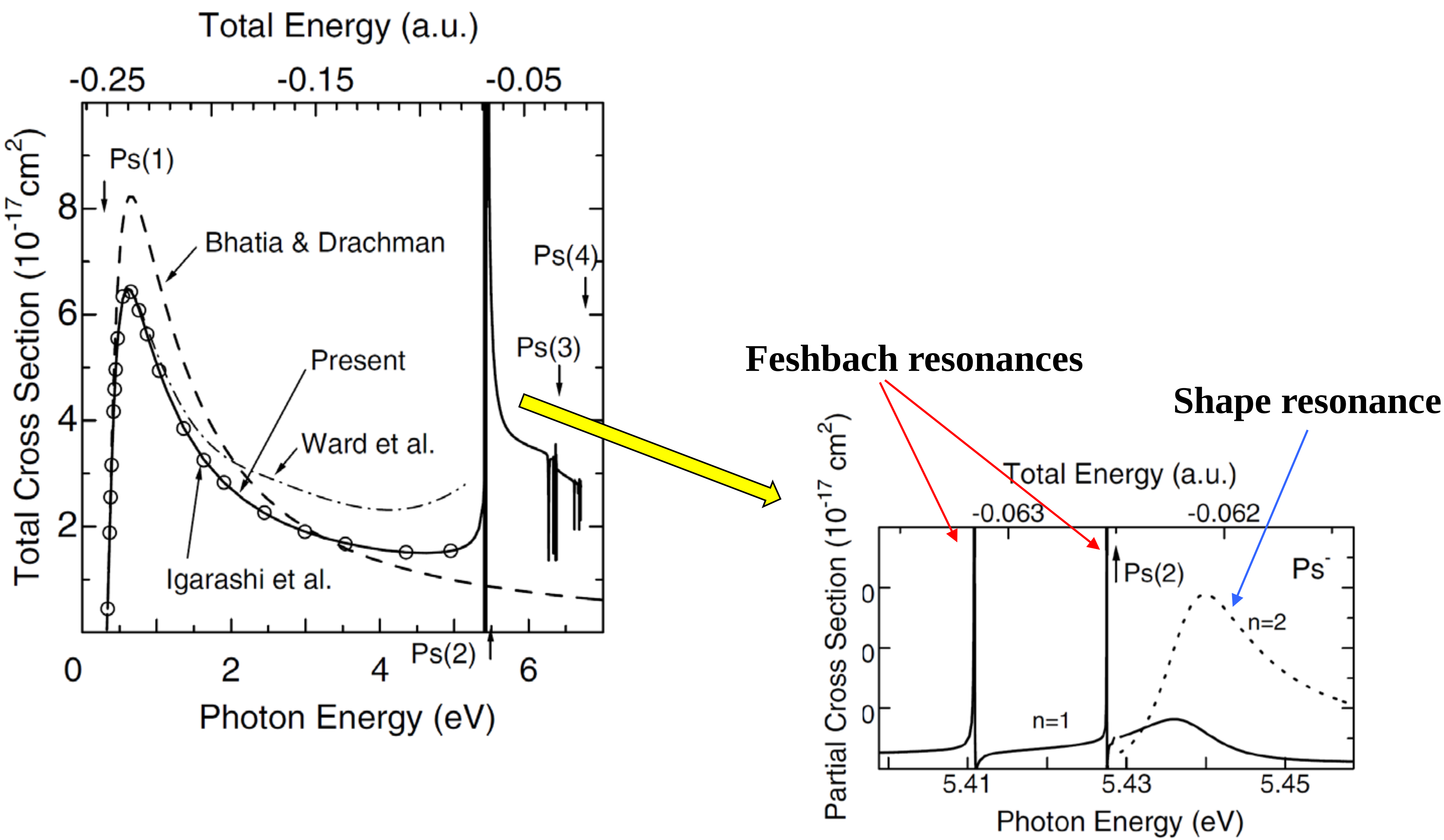
An electron linac was used to obtain a pulsed positron beam which can be synchronized with an intense pulse laser (Nd: YAG).



Backscattering geometry for efficient Ps⁻ production

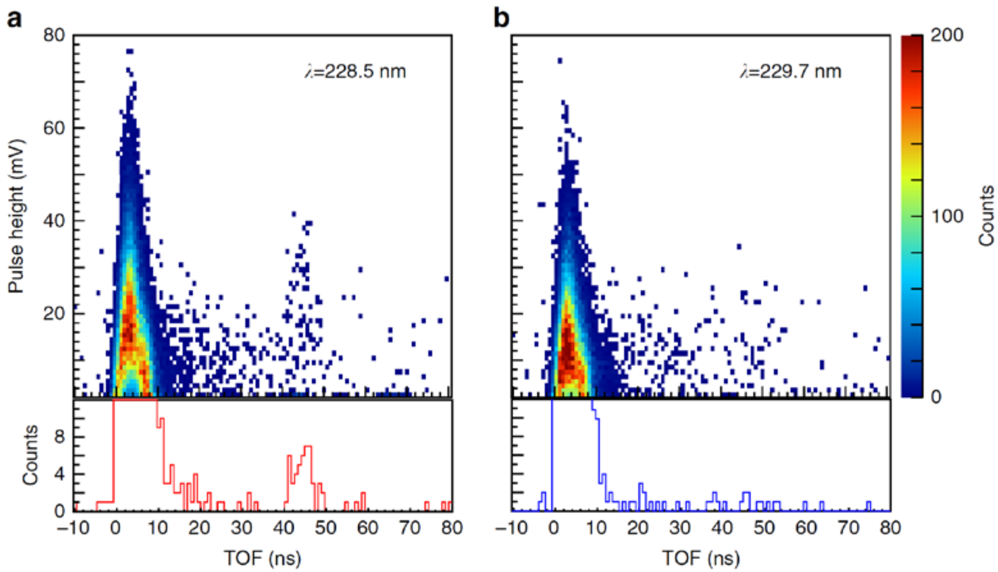
Michishio et al., APL (2012) 254102

Theories of Ps⁻ resonant photodetachment

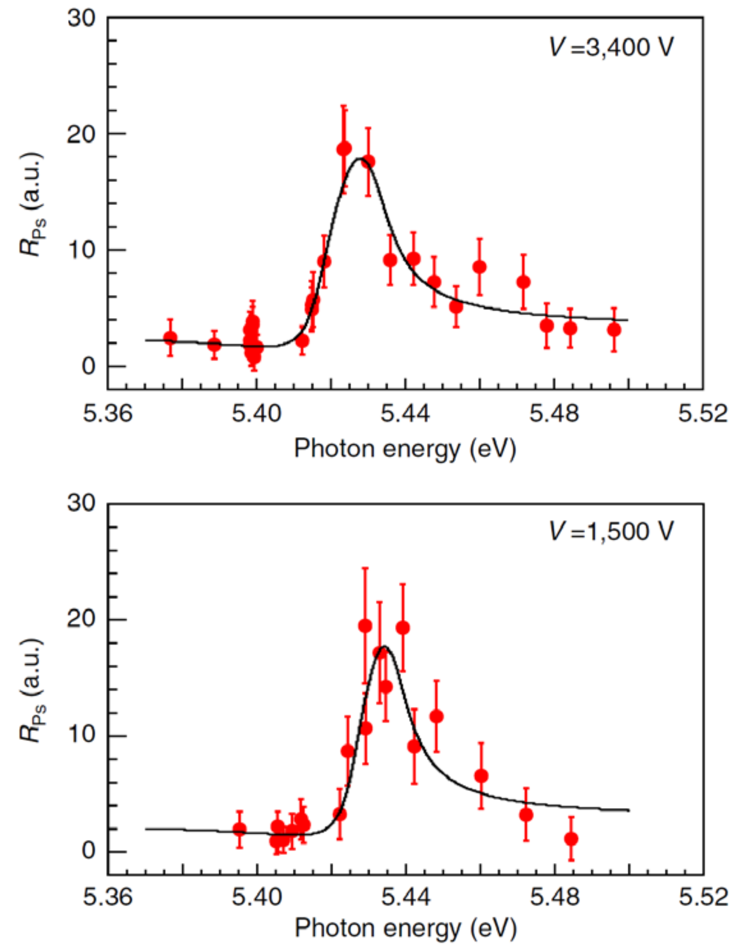


Total cross sections and partial cross sections
Igarashi, Toshima and Shimamura, NJP 2 (2000) 17

Observation of Ps^- resonant photodetachment



2D TOF spectra of the MCP signals.

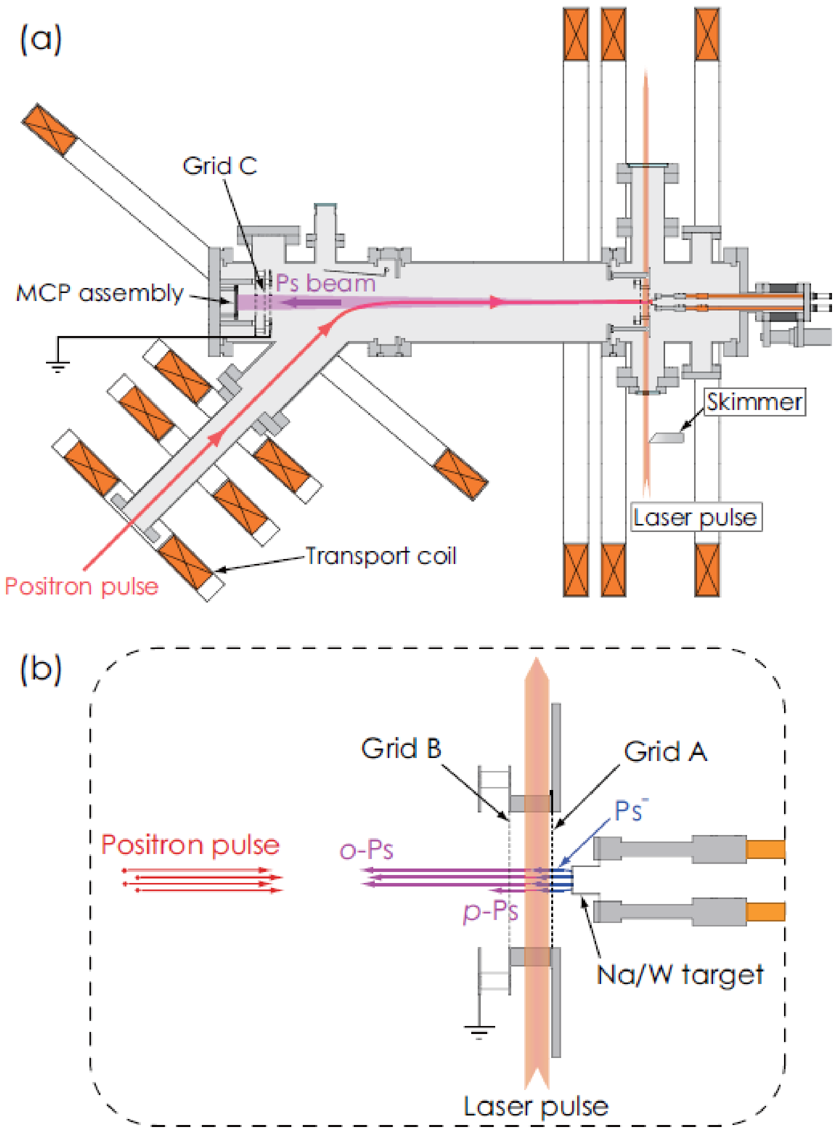


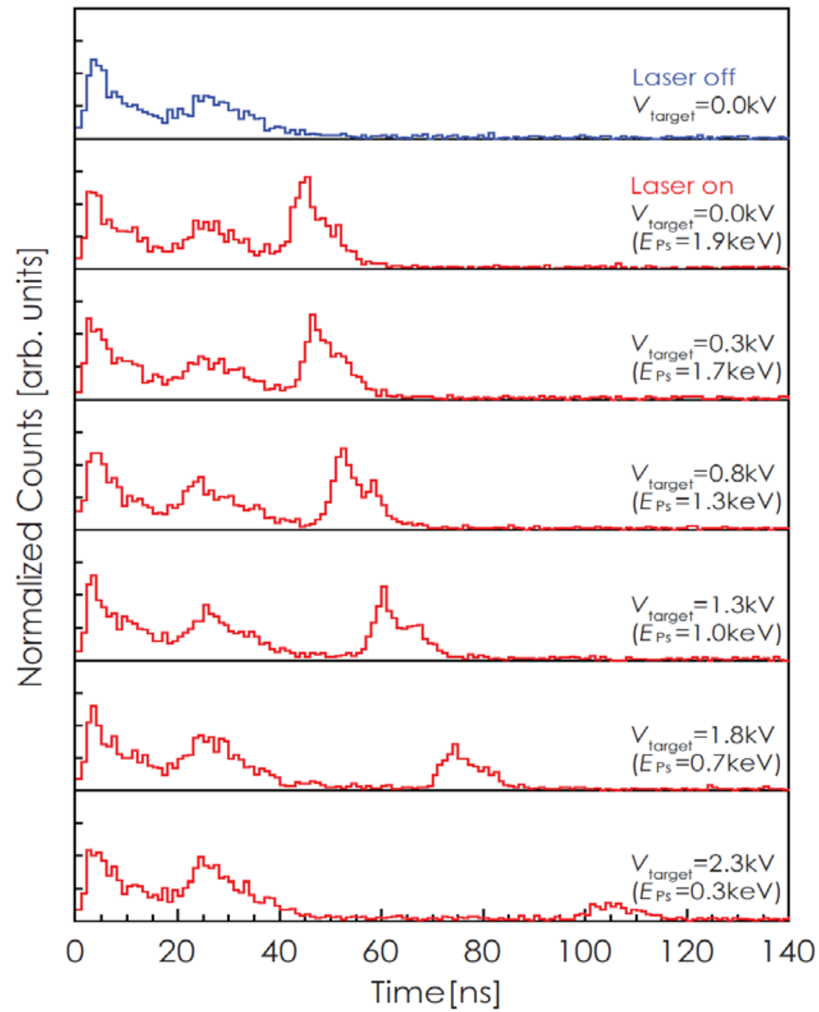
Resonance profiles o of Ps^-.

	Experiment	Theories		
Author(s)	**Present (2016)**	**Botero (1986)**	**Bhatia (1985)**	**Igarashi (2000)**
E_r **(eV)**	**5.437 (1)**	**5.44**	**5.438**	**5.4375**

Michishio et al., Nat. Commun. 7 (2016) 11060

Energy-tunable Ps beam produced via Ps⁻photodetachment





Michishio et al., APL (2012) 254102

Future plans:

- Observation of Feshbach resonances
  Precision measurement of Ps^- energy
- Measurement of the Ps^- photodetachment cross sections
  Measurement of the Ps^- binding energy
- Observation of Ps reflection from solid surfaces
- Observation of reflected high energy Ps diffraction
- Observation of quantum interference of Ps
  through two slits, grating, graphene

Key to the future of Ps beams:
Intense pulsed slow positron beam with intensity of ~ $10^{10} e^+/s$ or higher.

Intensities of the present slow positron beams: 10^5 – $10^8 e^+/s$

References:

Y. Nagashima et al., New J. Phys. 8 (2006) 319.
Y. Nagashima et al., New J. Phys. 10 (2008) 123079.
H. Terabe et al., New J. Phys. 14 (2012) 015003.
K. Michishio et al., Phys. Rev. Lett. 106 (2011) 153401.
K. Michishio et al., Appl. Phys. Lett. 100 (2012) 254102.
Y. Nagashima, Phys. Rep. 545 (2014) 95.
K. Michishio et al., Nat. Commun. 7 (2016) 11060.
K. Michishio et al., in preparation.

科研費　基盤研究(S)(24221006)、基盤研究(A)(17H01074)