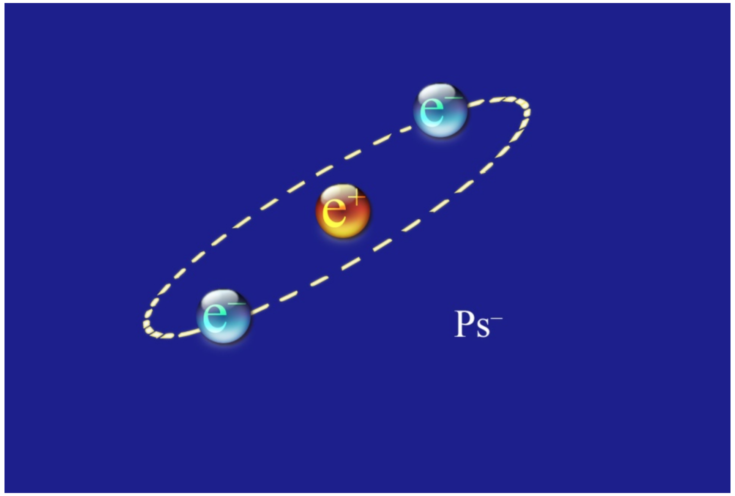
Recent experiments on positronium negative ions



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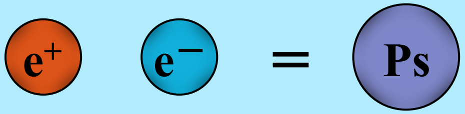
Department of Physics
Tokyo University of Science
JAPAN

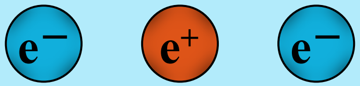
Positrons in Astrophysics

東京理科大学
TOKYO UNIVERSITY OF SCIENCE

Bound states composed of e^+ and e^-

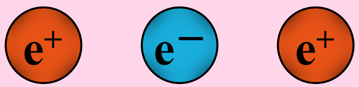


positronium (Ps)



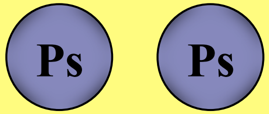
positronium negative ion (Ps^-)

Existence has been confirmed.



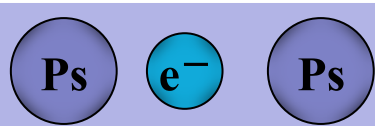
positronium positive ion (Ps^+)

Nobody has produced.

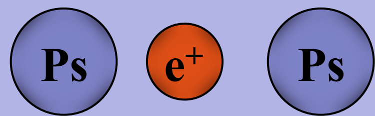


positronium molecule (Ps_2)

Existence has been confirmed by the Optical spectroscopy recently.
(Cassidy et al., accepted for publication in Phys. Rev. Lett.)



bi-positronium negative ion (Ps_2e^-)



bi-positronium positive ion (Ps_2e^+)

Theoretical study has been started.
(Frolov, Phys. Lett. A 372 (2008) 6721)

OUTLINE OF THIS TALK

- What is Ps^-?
- Measurement of the Ps^- decay rate
- Efficient formation of Ps^- using Na coated tungsten surface
- Ps^- photodetachment experiment
- Production of an energy tunable Ps beam
- Measurement of the Ps^- photodetachment cross section
- Production of Ps^+

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First prediction of Ps^{-} by John Wheeler (1946) :

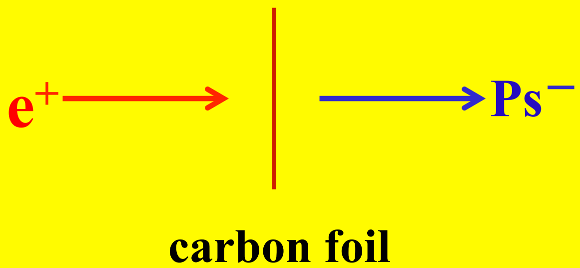
"The tri-electron system has a radioactive mean lifetime of the order of 10^{-10} sec., and is calculated to be stable by at least 0.19eV against dissociation into a bi-electron and a free electron or positron."

"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."

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

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

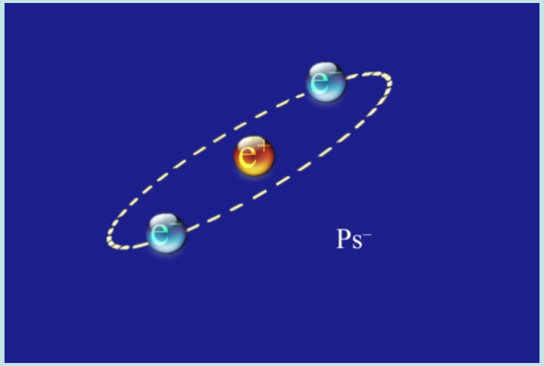
(Mills, Phys. Rev. Lett. 46 (1981) 717)



positronium (Ps)

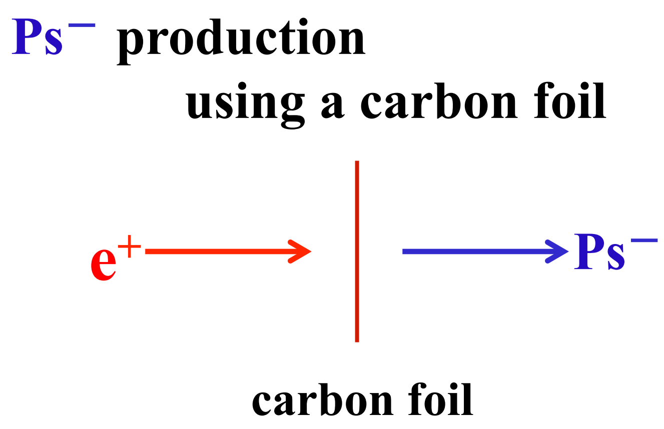
- ✓ H atom like state
- ✓ Binding energy : 6.80eV
- ✓ Mean distance e^{+} — e^{-} : $2a_0$
- ✓ Two eigenstates (ground states)
  - ortho-Ps (S=1, triplet)
    - lifetime in vacuum : 142ns
    - Self-annihilates into 3γ .
  - para-Ps (S=0, singlet)
    - lifetime in vacuum : 125ps
    - Self-annihilates into 2γ .

positronium negative ion (Ps^{-})



- ✓ H^{-} ion like state
- ✓ 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.

Ps^- production using a carbon thin foil



Production efficiency ~ 0.028%

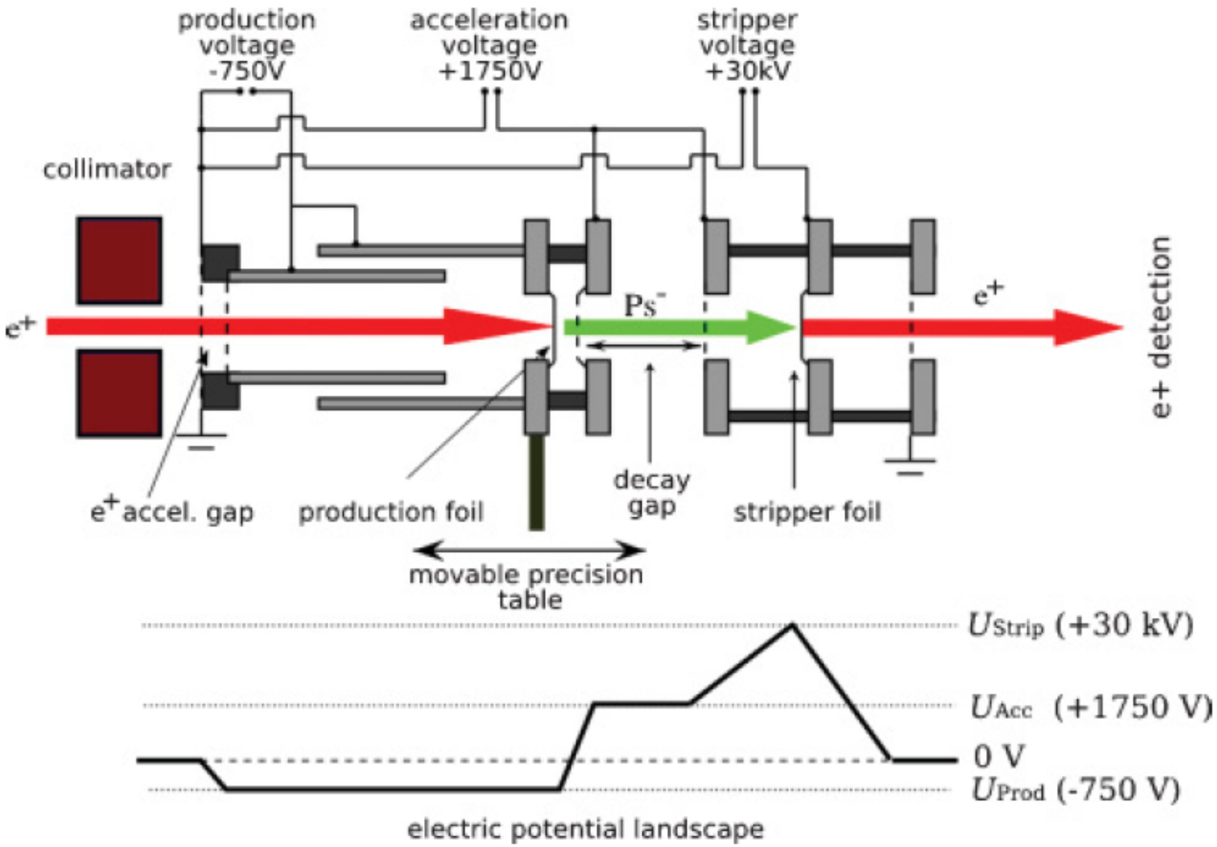
✓ **Measurements of the Ps^- decay rate**

Mills (Bell Lab.)
Fleischer et al. (Max Planck)
Ceeh et al. (Munich)

Measurement of the Ps⁻ decay rate (Munich)

target : DLC (diamond-like-carbon)

Insense slow e⁺ beam at the NEPOMUC



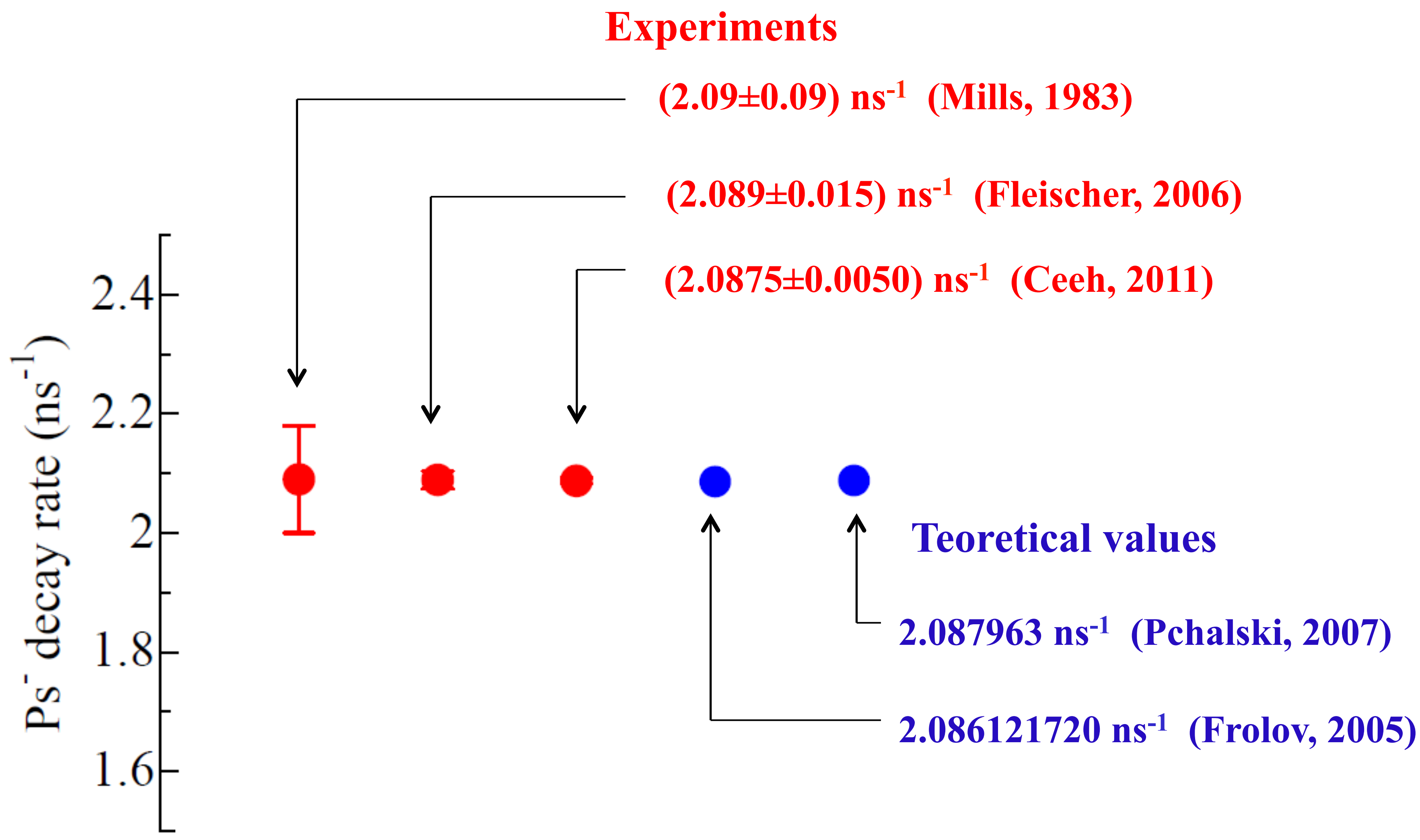
Ps⁻ production efficiency ~ 1 x 10⁻⁴

Stripping-based detection technique (Mills 1989)

$$\Gamma = (2.0875 \pm 0.0050)\, ns^{-1}$$

(Ceeh et al., Phys. Rev. A 84 (2011) 062508)

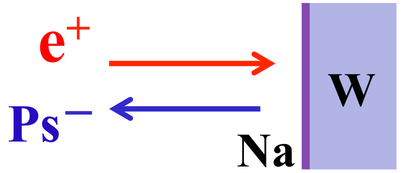
Measurements of Ps^- decay rate – comparison with theoretical values



All the experimental values are consistent with recent theoretical values.

Ps^- production using alkali metal coated tungsten surfaces

Ps^- production using Na coated tungsten surfaces



efficiency

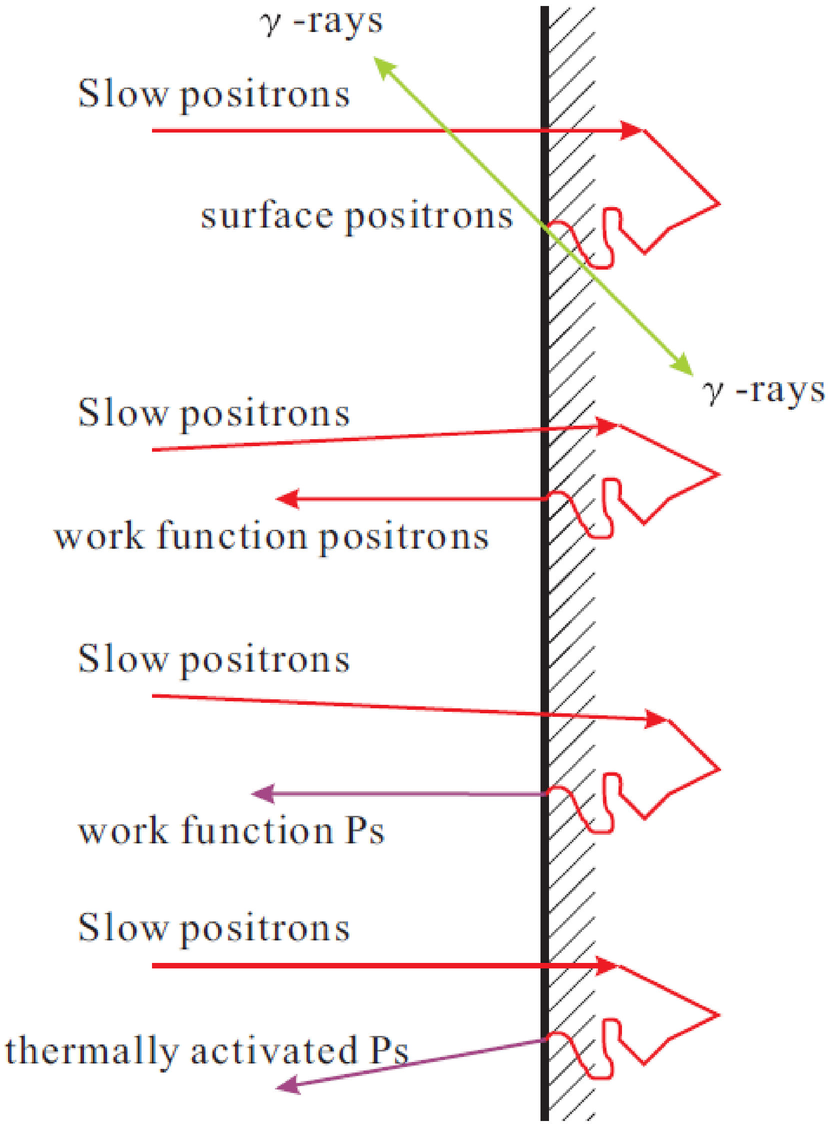
~ 1.5%

✓Observation of Ps^- photodetachment

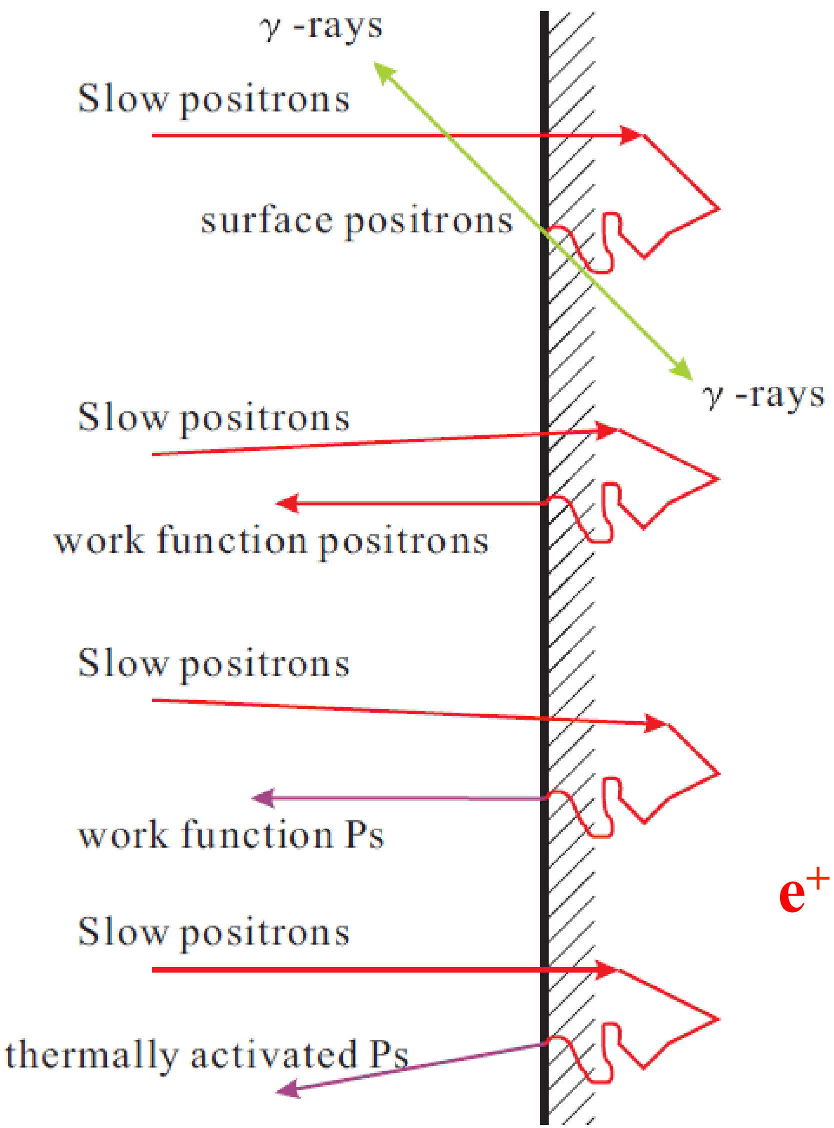
✓ Measurement of the Ps^- photodetachment cross sections

✓ Production of an energy tunable Ps beam

Tokyo University of Science, KEK



γ -rays
Slow positrons
surface positrons
γ -rays
Slow positrons
work function positrons
Slow positrons
work function Ps
Slow positrons
thermally activated Ps



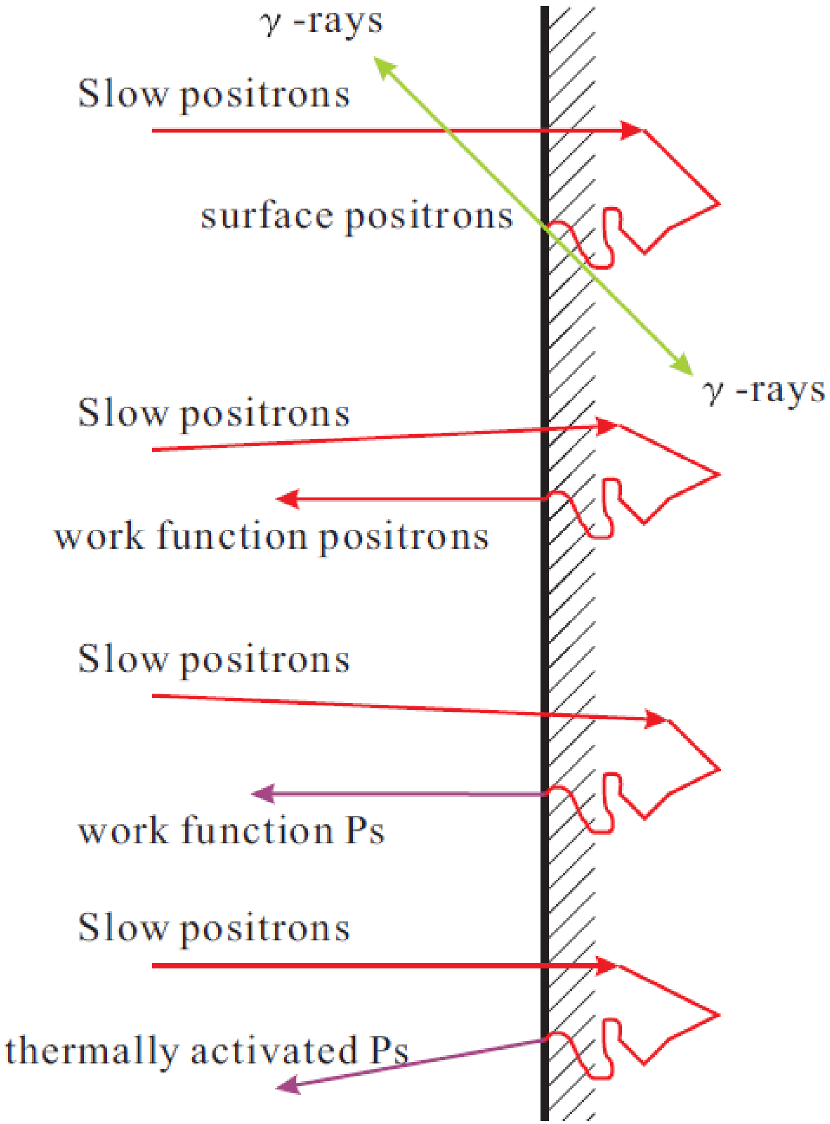
ϕ_+ : **e⁺ work function**

(The energy required to emit e⁺)

$$\phi_+ < 0$$

⇓

e⁺ are emitted from the surface.



The energy required to emit Ps :

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

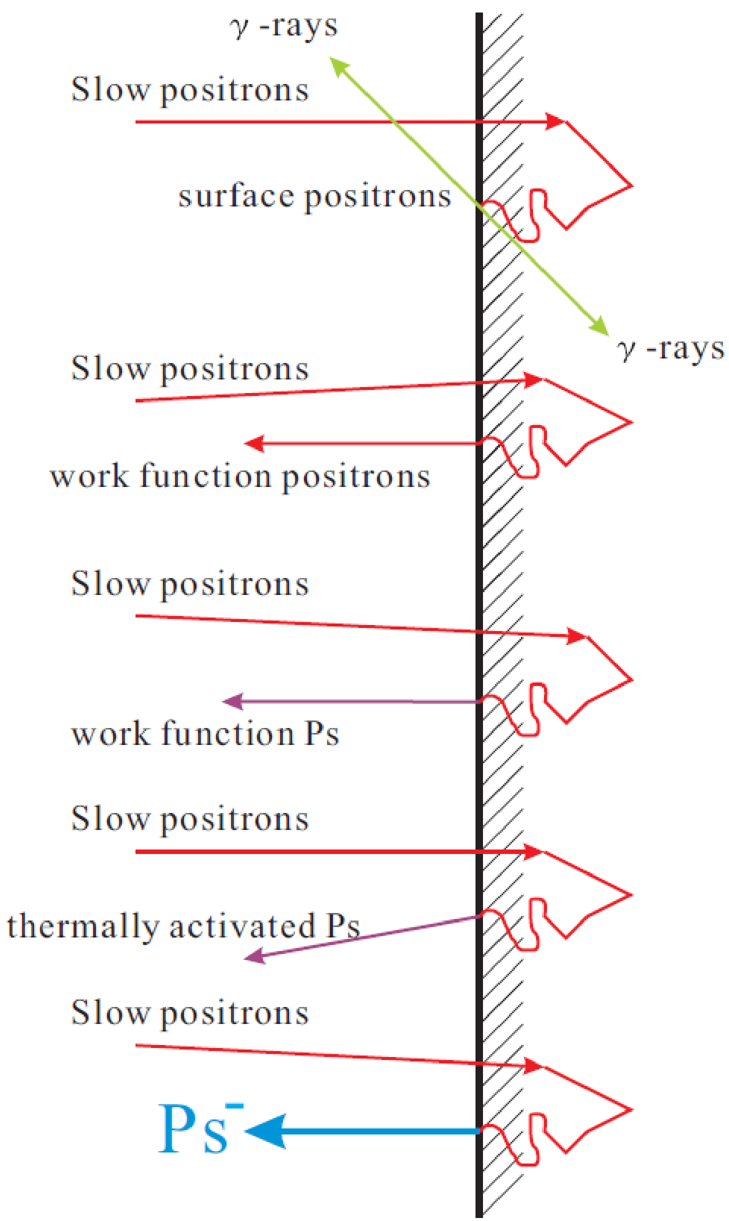
ϕ_+ : **e^+ work function**

ϕ_- : **e^- work function**

$$\phi_{Ps} < 0$$

⇓

Ps atoms are emitted from the surface.



The energy required for Ps^- emission :

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

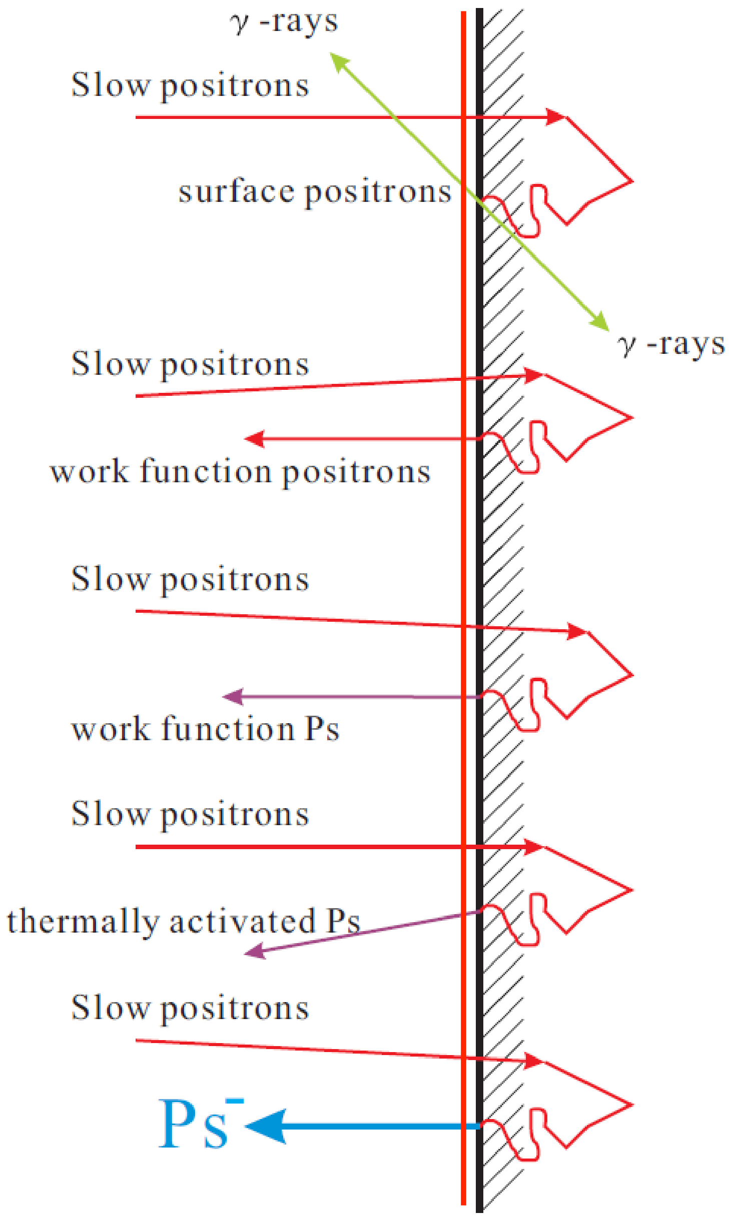
- e^+ work function (ϕ_+)
- e^- work function (ϕ_-)
- The energy required to break up Ps^- into three isolated particles
=(Ps binding energy, 6.80eV)
+(e^- binding energy to Ps, 0.33eV)

For tungsten, $\phi_{Ps^-} < 0$

⇩

Ps^- is emitted from the surface spontaneously.

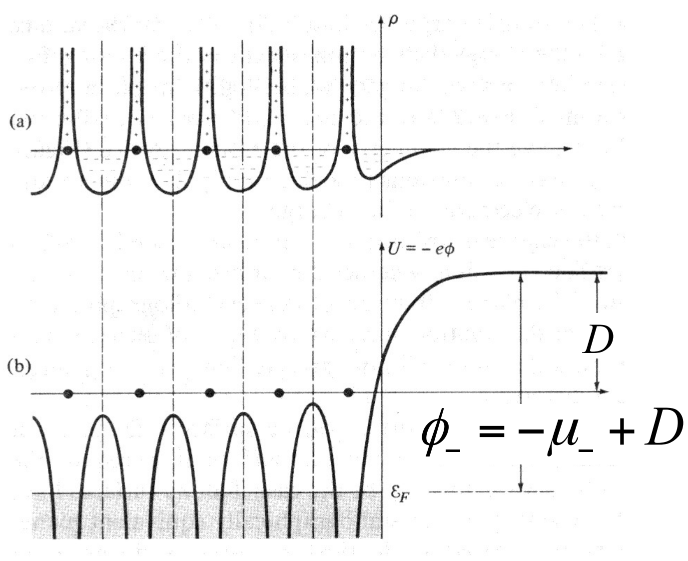
Formation efficiency < 0.01%

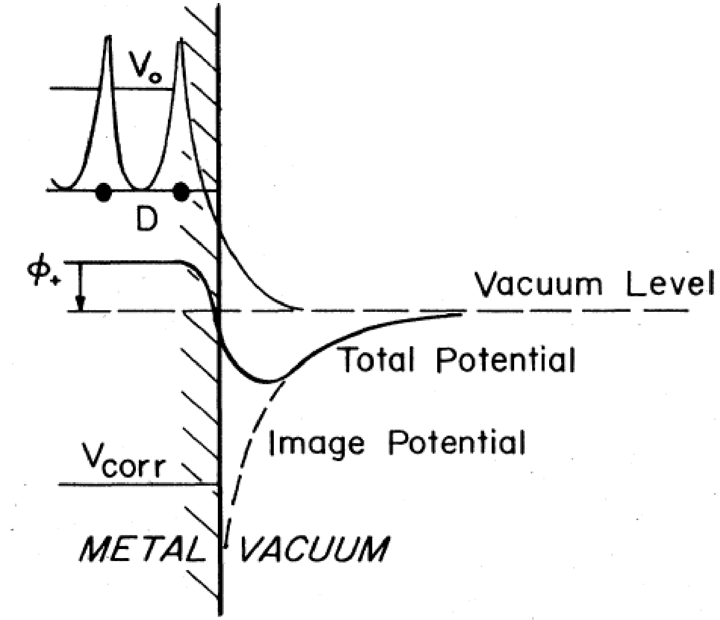


By coating alkali metals onto the surface, the efficiency increases dramatically.

~1.5%

e^- and e^+ near metal surface





e^- energy level

(Achcroft and Mermin)

e^+ energy lebel

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

e^- work function : $\phi_- = -\mu_- + D$

e^+ work function : $\phi_+ = -\mu_+ - D$

μ_- : **e^- chemical potential**

μ_+ : **e^+ chemical potential**

D : **effect of surface dipole**

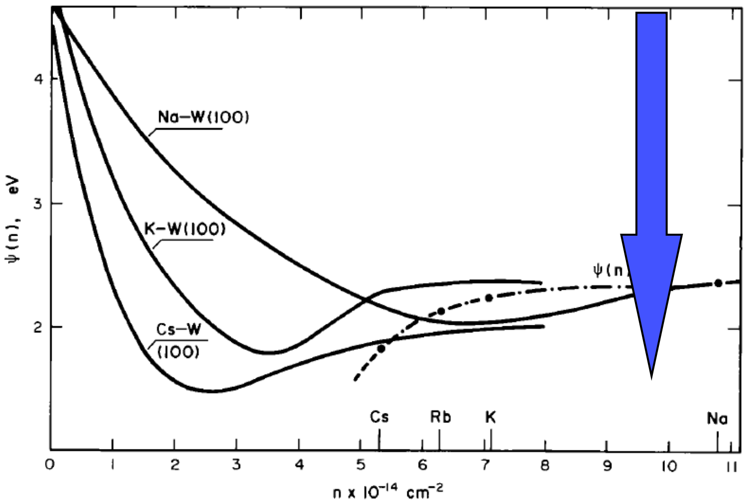
The energy required for Ps^- emission :

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

Effect of alkali metal coating for the Ps⁻ emission

Change of ϕ_- for tungsten by alkali metal coating

***D* decreases.**



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

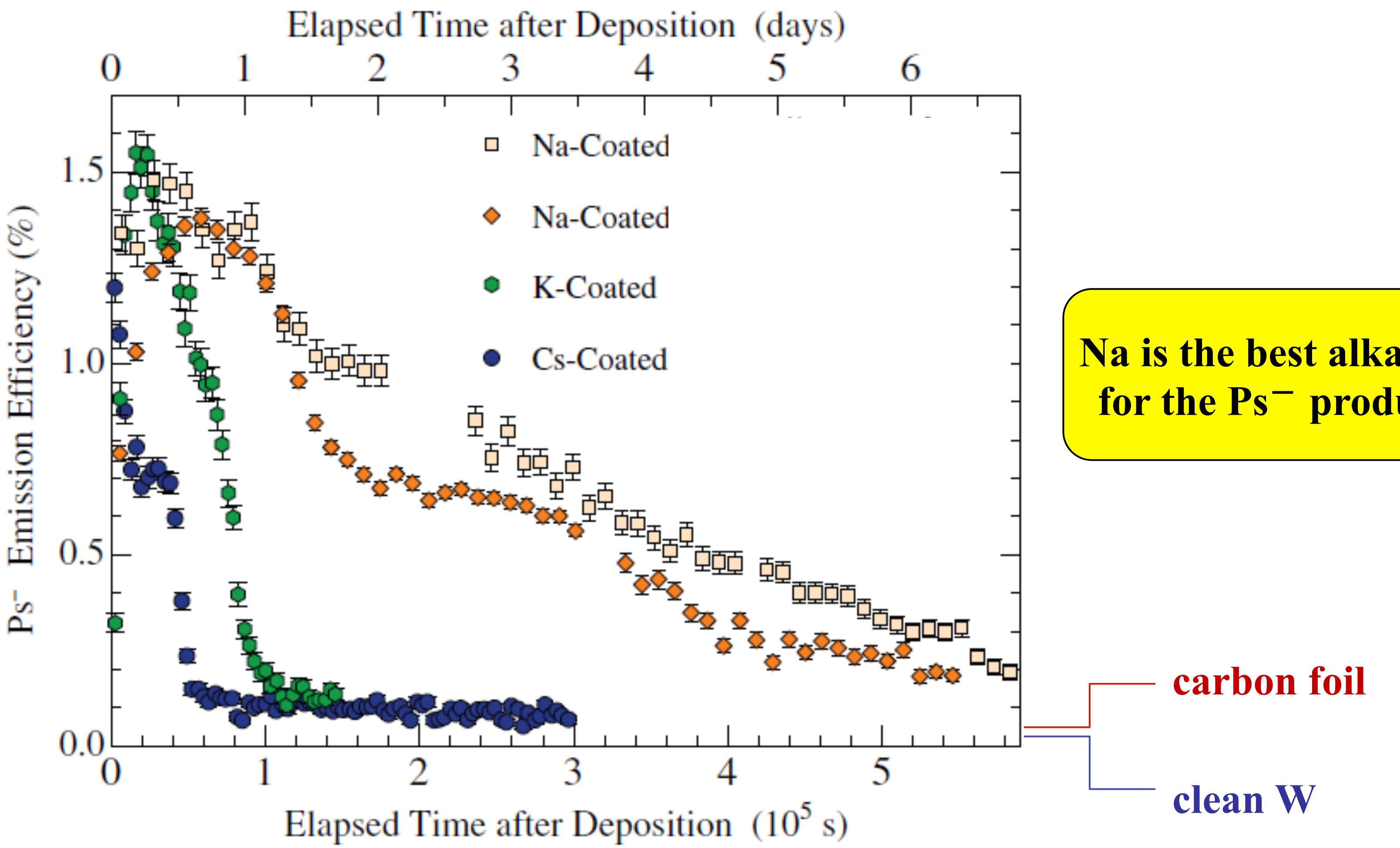
***D* decreases by alkali metal coating.**

$\phi_{Ps^-} = -\mu_+ - 2\mu_- + D - 7.13\,\text{eV}$ **decreases.**

The fraction of conduction electrons available for the Ps⁻ production increases.

Ps⁻ emission efficiency increases.

Effect of alkali metal coating for the Ps⁻ emission



Na is the best alkali metal for the Ps⁻ production.

Terabe, Michishio, Tachibana and Nagashima, New J. Phys. 14 (2012) 015003

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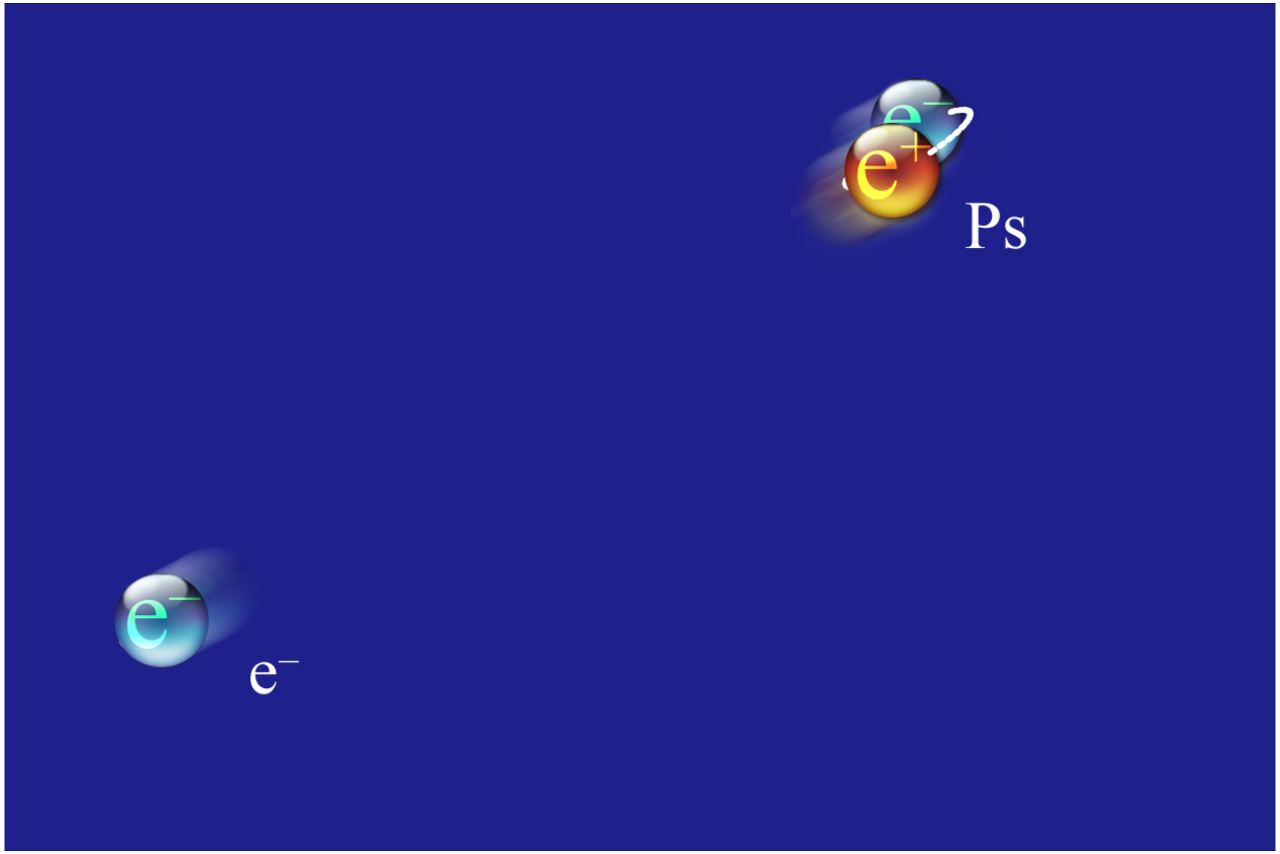


e⁻
e⁺
Ps
e⁻
e⁻

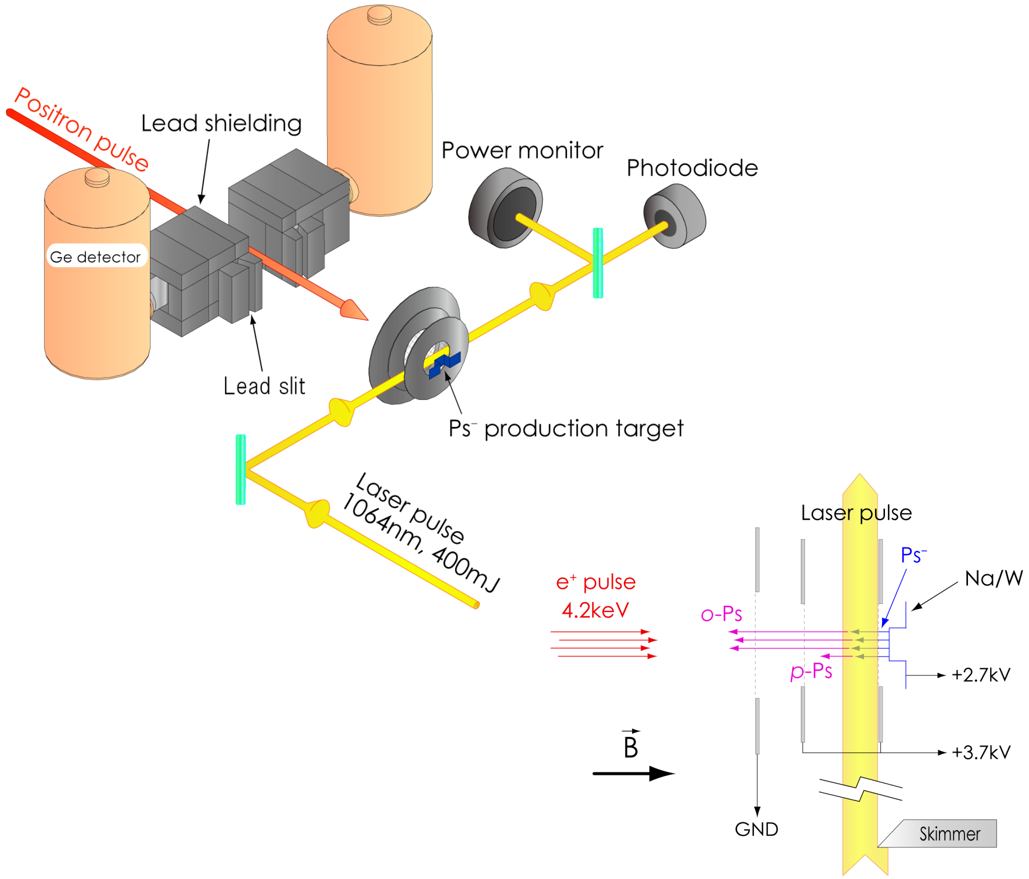
Ps^- photodetachment experiment

Ps^- lifetime is 479ps.

High intensity pulsed laser

Pulsed e^+ beam synchronized to the laser

Ps$^-$ photodetachment experiment



e^+ beam :

(from KEK Linac)

pulse width	**12ns**
repetition	**50pps**
beam intensity	**$5\times10^5 e^+/s$**

Laser :

Q-switched Nd: YAG

(Spectra Physics GCR290)

wave length	**1064nm (1.165eV)**
pulse width	**12ns**
repetition	**25pps**
power10W	

(Michishio, Tachibana, Terabe, Igarashi, Wada, Hyodo, Kuga, Yagishita, Hyodo and Nagashima Phys. Rev. Lett. 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.

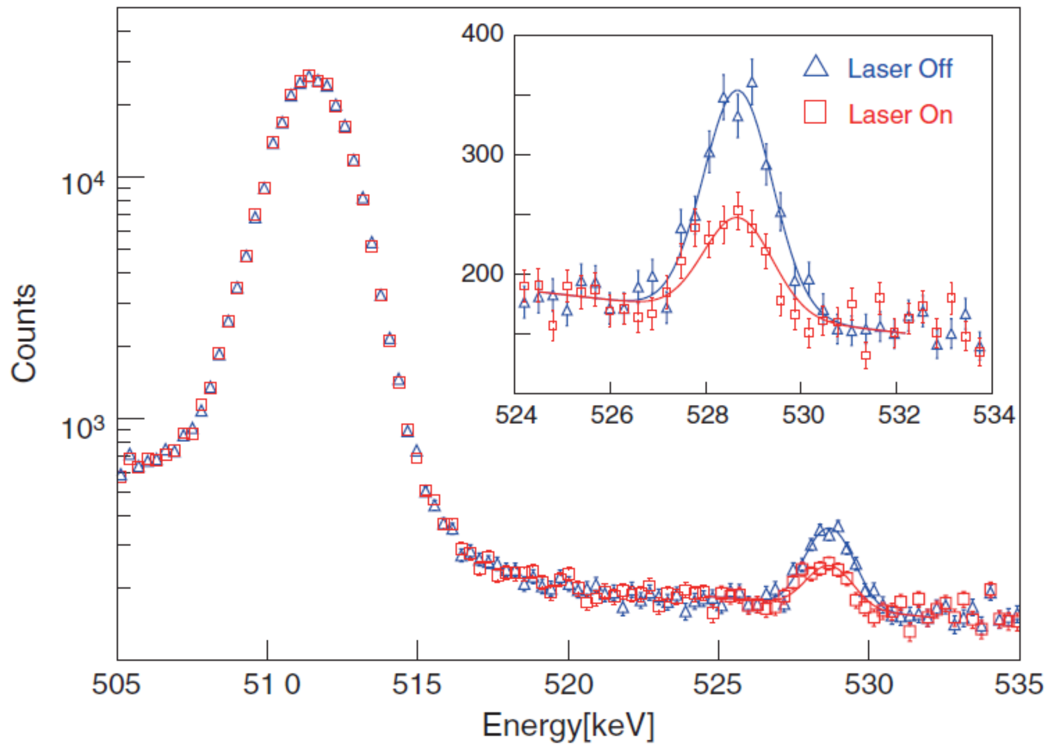
(Michishio, Tachibana, Terabe, Igarashi, Wada, Hyodo, Kuga, Yagishita, Hyodo and Nagashima
Phys. Rev. Lett. 106 (2011) 153401)

Ps^- photodetachment experiment

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

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

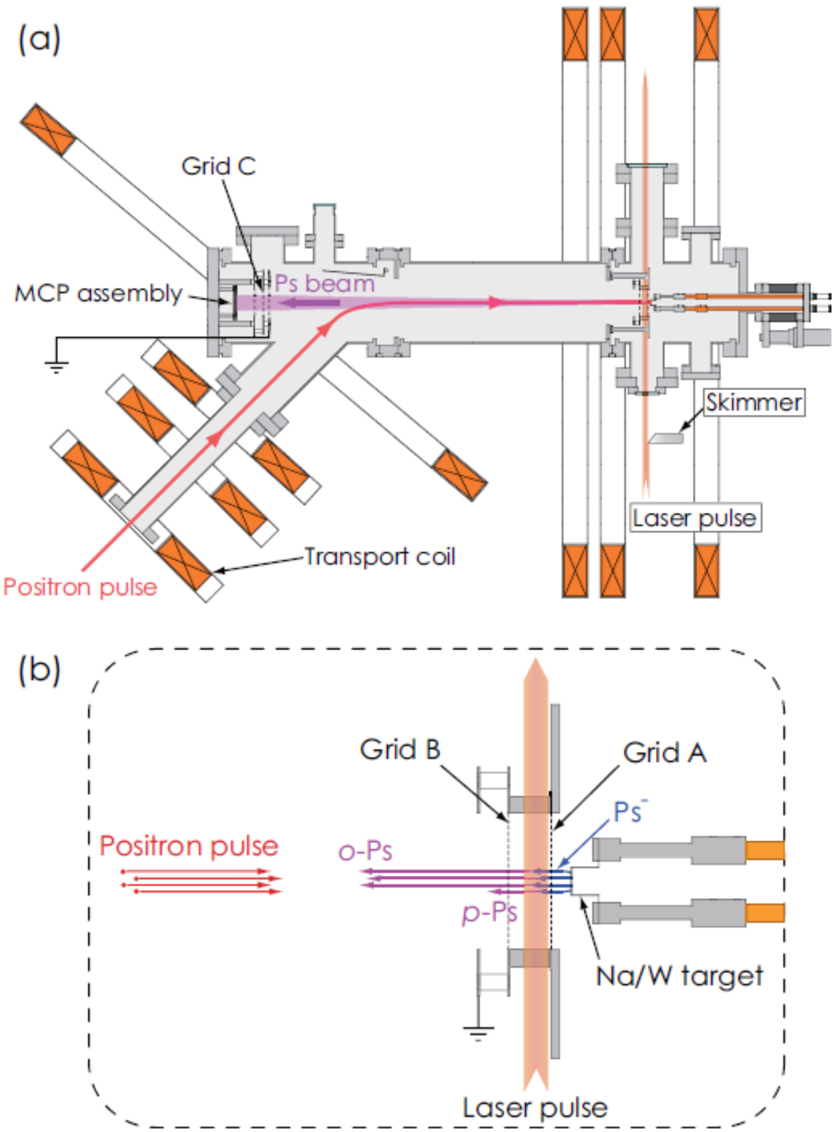
If Ps^- ions are photodetached, the peak intensity will decrease.



Ps^- photodetachment has been observed for the first time!

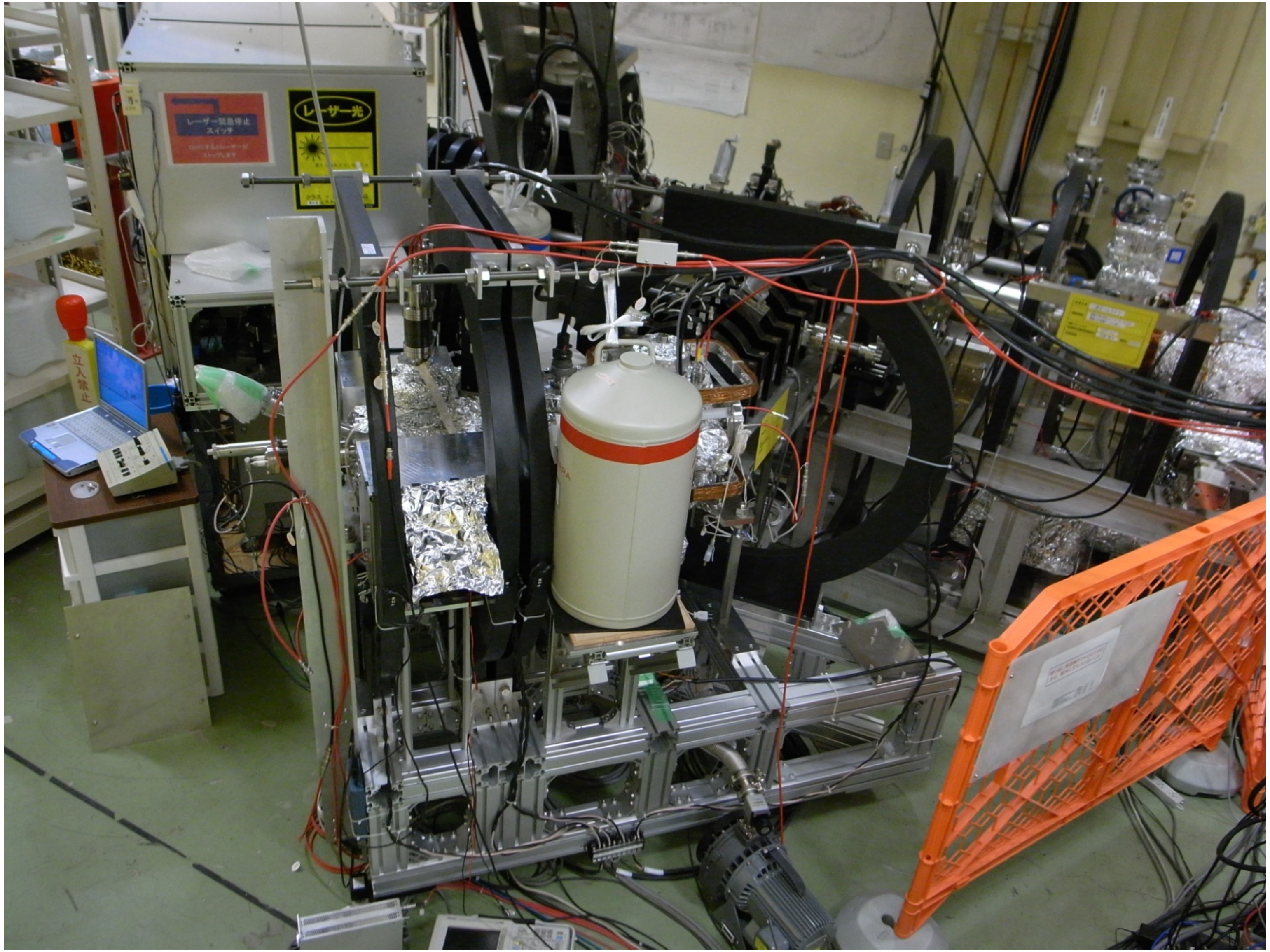
(Michishio, Tachibana, Terabe, Igarashi, Wada, Hyodo, Kuga, Yagishita, Hyodo and Nagashima Phys. Rev. Lett. 106 (2011) 153401)

Detection of Ps produced by the Ps$^-$ photodetachment

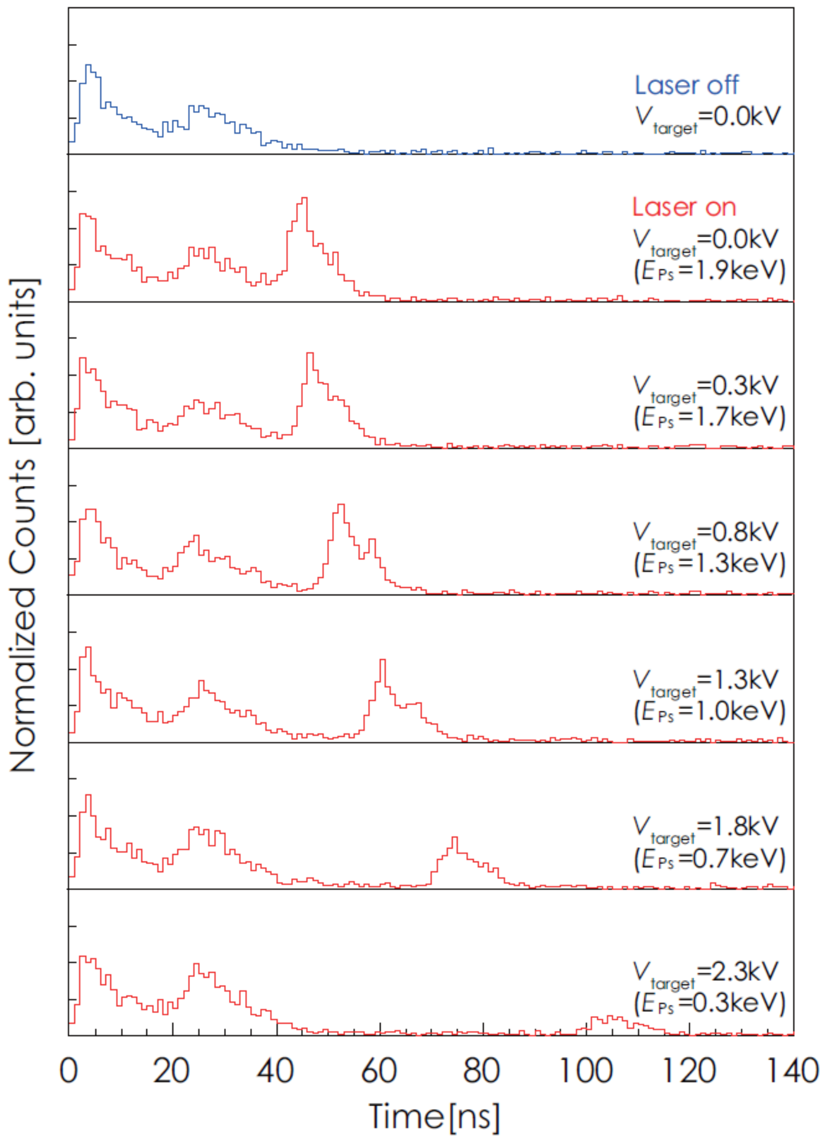


Michishio et al., submitted to Appl. Phys. Lett.

Detection of Ps produced by the Ps^{-} photodetachment

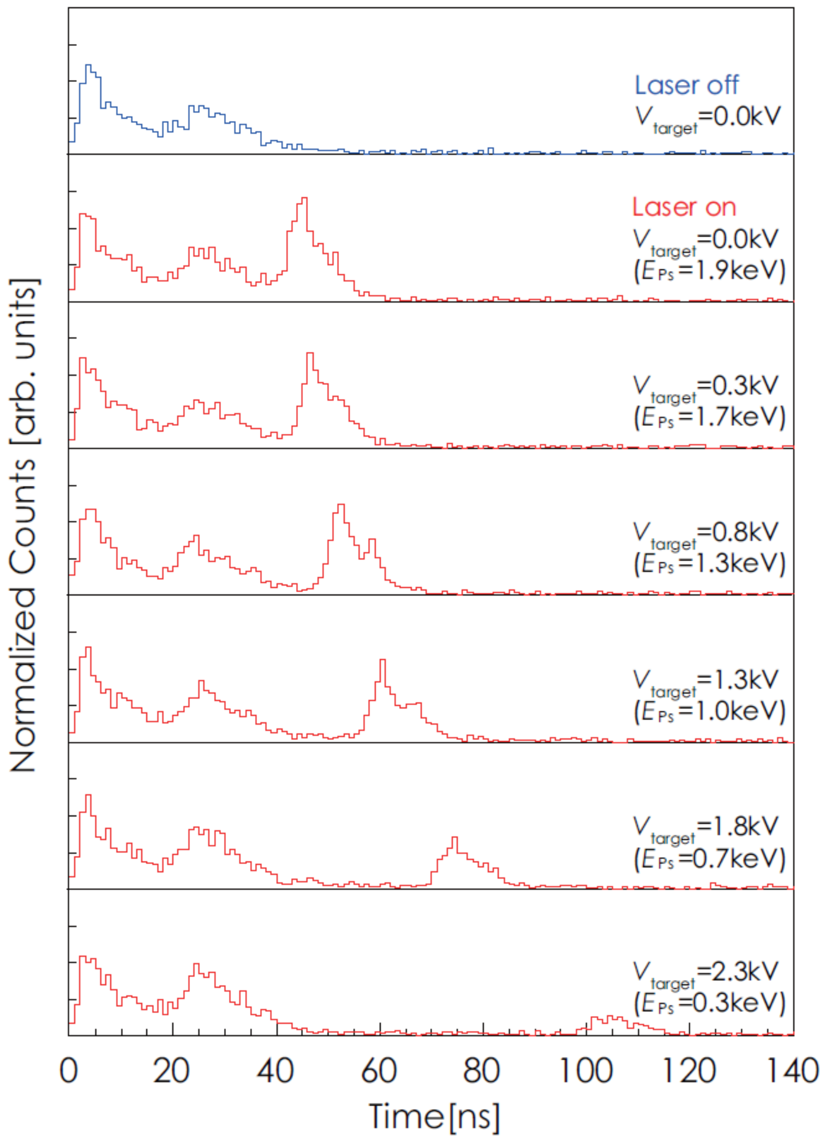


Detection of Ps produced by the Ps⁻photodetachment



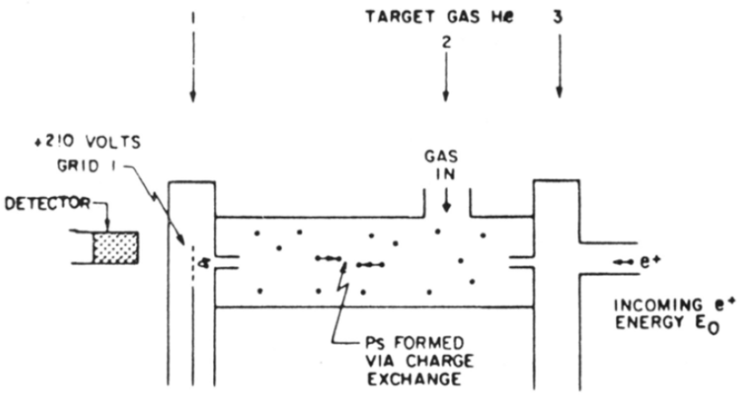
Michishio et al., submitted to Appl. Phys. Lett.

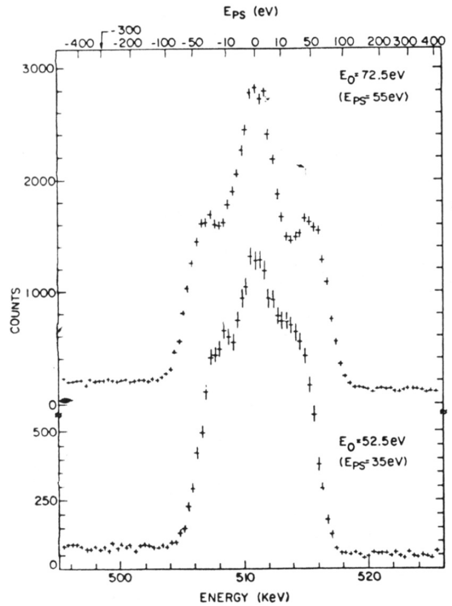
Energy tunable Ps beam using the Ps⁻ photodetachment



Michishio et al., submitted to Appl. Phys. Lett.

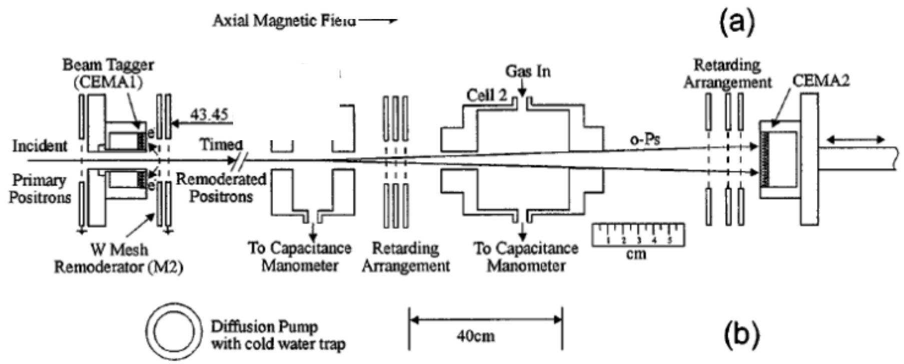
Energy tunable Ps beam using charge exchange with atoms





(Brown, Positron Annihilation (1985) 328)

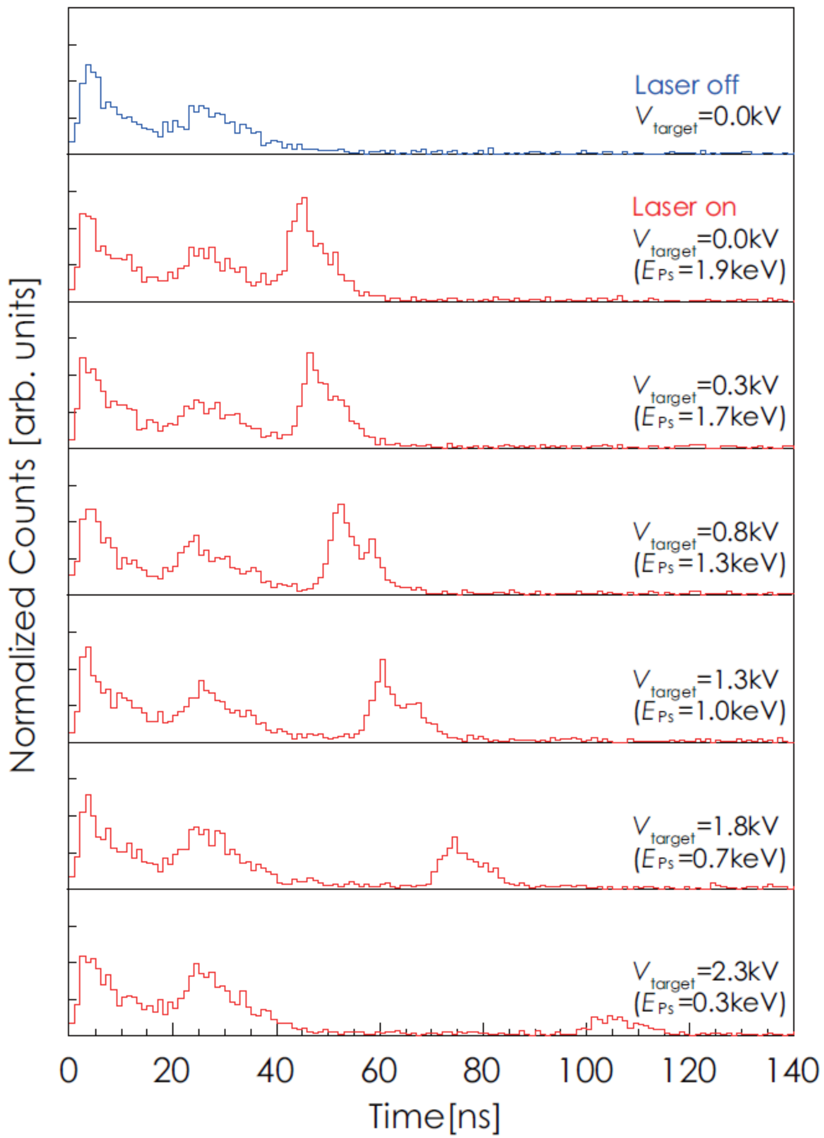
Energy tunable **Ps beam**
for the **Ps-gas scattering (UCL group)**



Energy range < 400eV

Next talk

Energy tunable Ps beam using the Ps^- photodetachment



Energy range : 300eV − 28keV
UHV compatible

Michishio et al., submitted to Appl. Phys. Lett.

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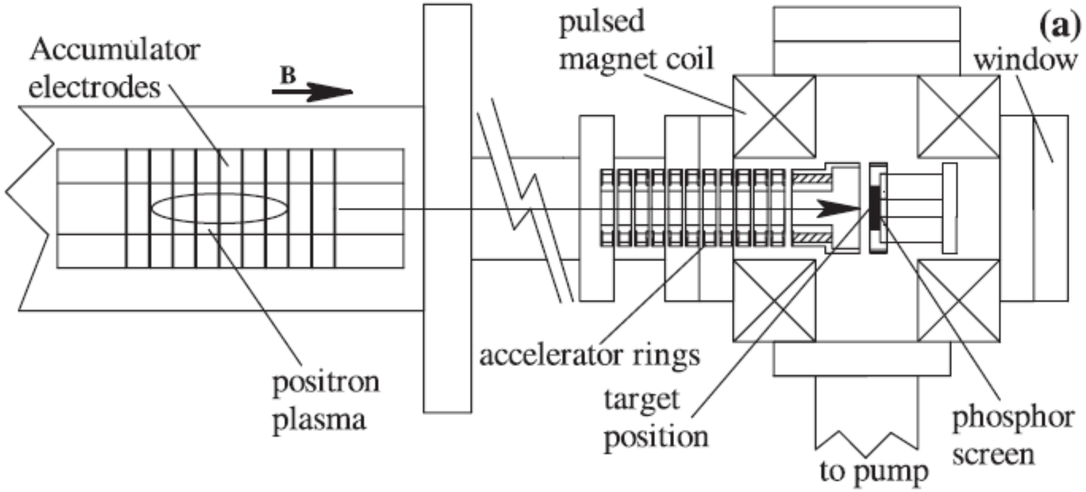
- **Production of Ps^+**

Production of Ps^- and Ps^+ using Ps_2



$$Ps_2 + \text{photon} \rightarrow \begin{cases} Ps^- + e^+ \\ Ps^+ + e^- \end{cases}$$

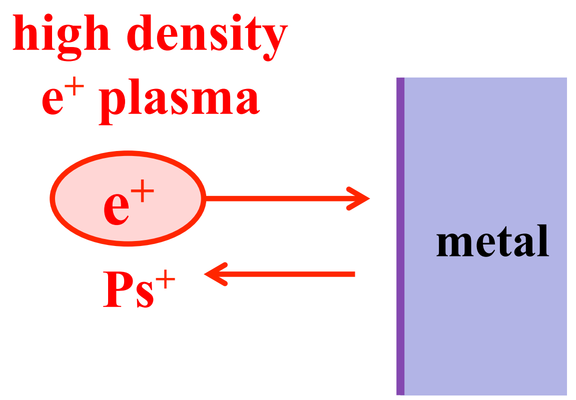
D. Cassidy et al., Phys. Rev. Lett. 95 (2005) 195006;
to be published in Phys. Rev. Lett.

Production of Ps^+ using metal surfaces (future plan)

Element	ϕ_{Ps^-} (eV)	ϕ_{Ps^+} (eV)
C (graphite)	4.3	0.7
Al (polycrystalline)	1.2	−3.3
Al (100)	1.11	−3.25
Al (111)	1.46	−2.74
Cr (100)	0.03	−6.19
Fe (polycrystalline)	0.5	−5.1
Co (polycrystalline)	2.1	−3.7
Ni (polycrystalline)	2.0	−4.4
Ni (100)	2.3	−3.9
Ni (110)	1.6	−4.9
Cu (100)	2.8	−2.6
Cu (110)	1.6	−3.1
Cu (111)	2.4	−3.0
Mo (polycrystalline)	−0.1	−6.9
Mo (100)	0.2	−6.0
Ag (100)	2.8	−1.3
W (polycrystalline)	−0.78	−8.08
W (100)	−0.9	−8.5
W (110)	0.3	−7.9
W (111)	−0.82	−7.86
Pt (polycrystalline)	2.4	−5.1
Au (polycrystalline)	4.2	−0.1
Pb (polycrystalline)	2.3	−1.1

The energy required for Ps^+ emission :

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



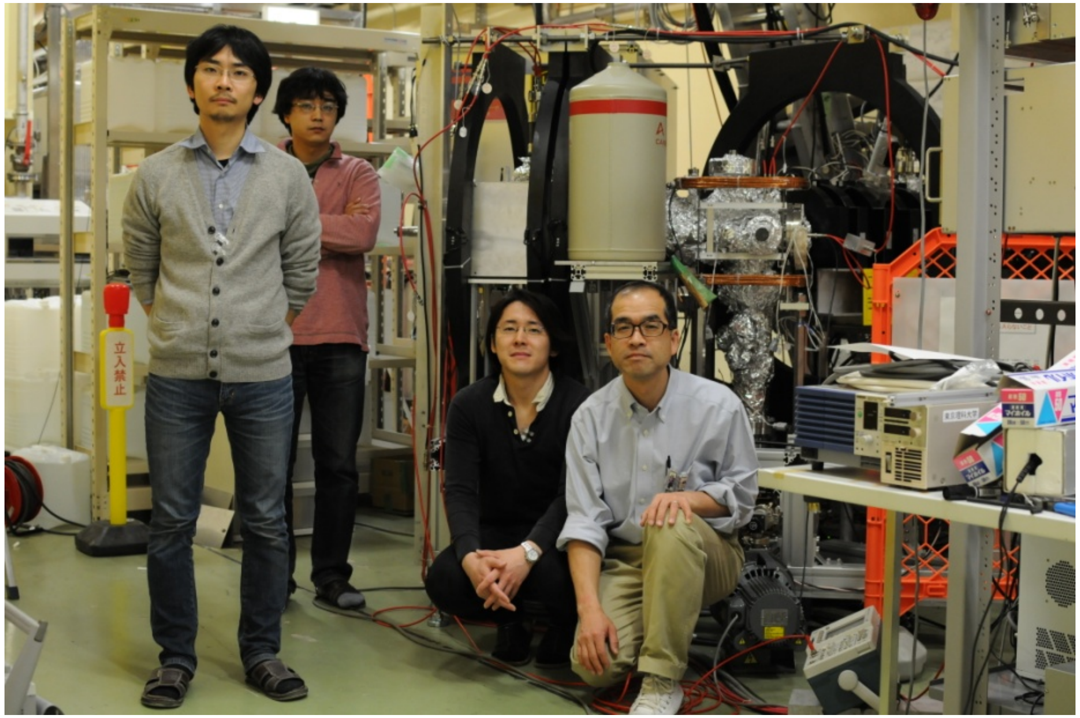
Y. Nagashima, NIMB 266 (2008) 511

Members of our group

Tokyo University of Science

Koji Michishio, Takayuki Tachibana
Hiroki Terabe, Ryohei Suzuki
Ayaka Miyamoto, Toshihide Hakodate
Takahiko Sakai

Akira Yagishita (KEK)
Toshio Hyodo (KEK)
Ken Wada (KEK)
Akinori Igarashi (Miyazaki Univ.)



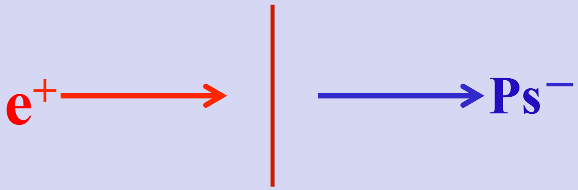
Thank you for your attention !

Theoretical investigations :

1946	Prediction of the existence of Ps^- by Wheeler
1960	Calculation of the Ps^- binding energy by Kolos, Rootrhaan and Sack.
1964	Calculation of the Ps^- binding energy by Frost, Inokuti and Lowe.
1968	Calculation of the Ps^- decay rate by Ferrante.
1979	Calculation of the Ps^- binding energy by Ho.
1983	Calculation of the Ps^- binding energy and the decay rate by Bhatia and Drachman.
1987	Calculation of the Ps^- photodetachment cross sections by Ward, Humberston and McDowell.
1990	Calculation of the Ps^- decay rate by Ho.
1993	Calculation of the Ps^- binding energy by Ho.
2000	Calculation of the Ps^- binding energy by Korobov.
2000	Calculation of the Ps^- photodetachment cross sections by Igarashi, Shimamura and Toshima.
2002	Calculation of the Ps^- binding energy by Drake, Grigorescu and Nistor.
2005	Calculation of the Ps^- binding energy by Drake and Grigorescu.
2005	Calculation of the Ps^- decay rate by Frolov.
2007	Calculation of the Ps^- decay rate by Puchalski and Czanecki.

Experiments on Ps$^-$

Ps$^-$ production using a carbon foil



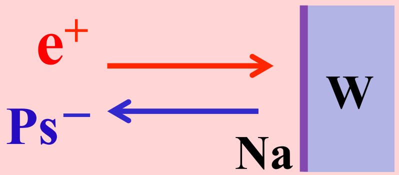
carbon foil

Production efficiency ~ 0.028%

✓ Measurement of the Ps$^-$ decay rate

Bell Lab.
Max-Planck
Munich

Ps$^-$ production using Na coated tungsten surfaces



Production efficiency ~ 1%

✓ Ps$^-$ photodetachment

✓ Ps$^-$ photodetachment cross sections

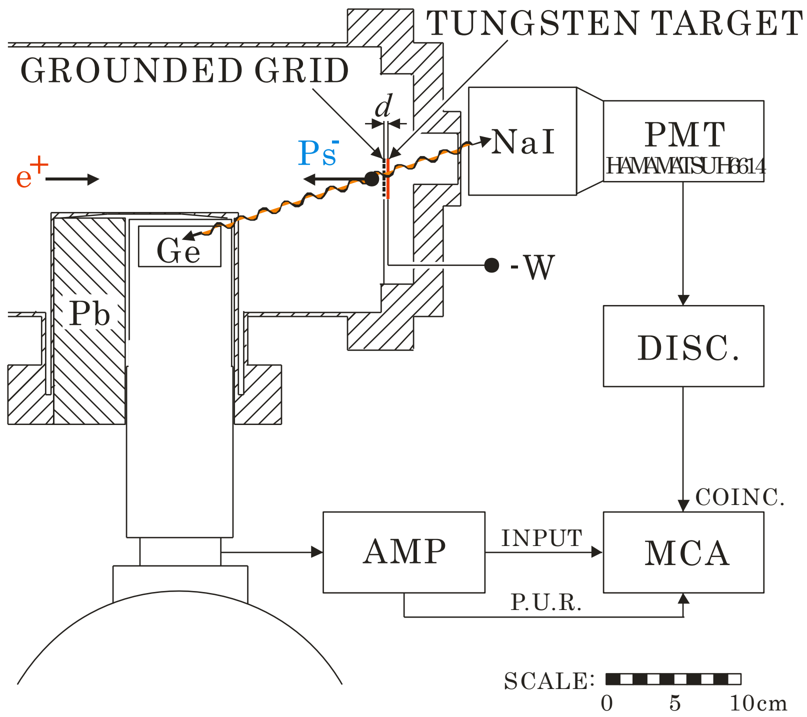
✓ Production of an energy tunable Ps beam

✓ Measurement of the Ps$^-$ decay rate is planned.

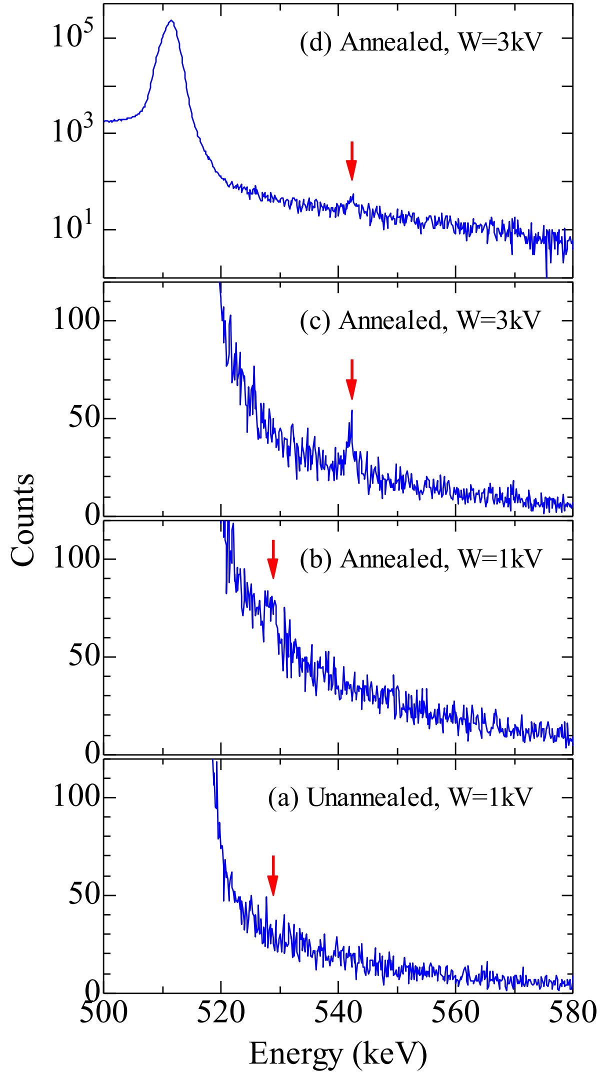
Tokyo University of Science, KEK

Ps⁻ emission from polycrystalline tungsten surface

(Nagashima and Sakai, New J. Phys. 8 (2006) 319)

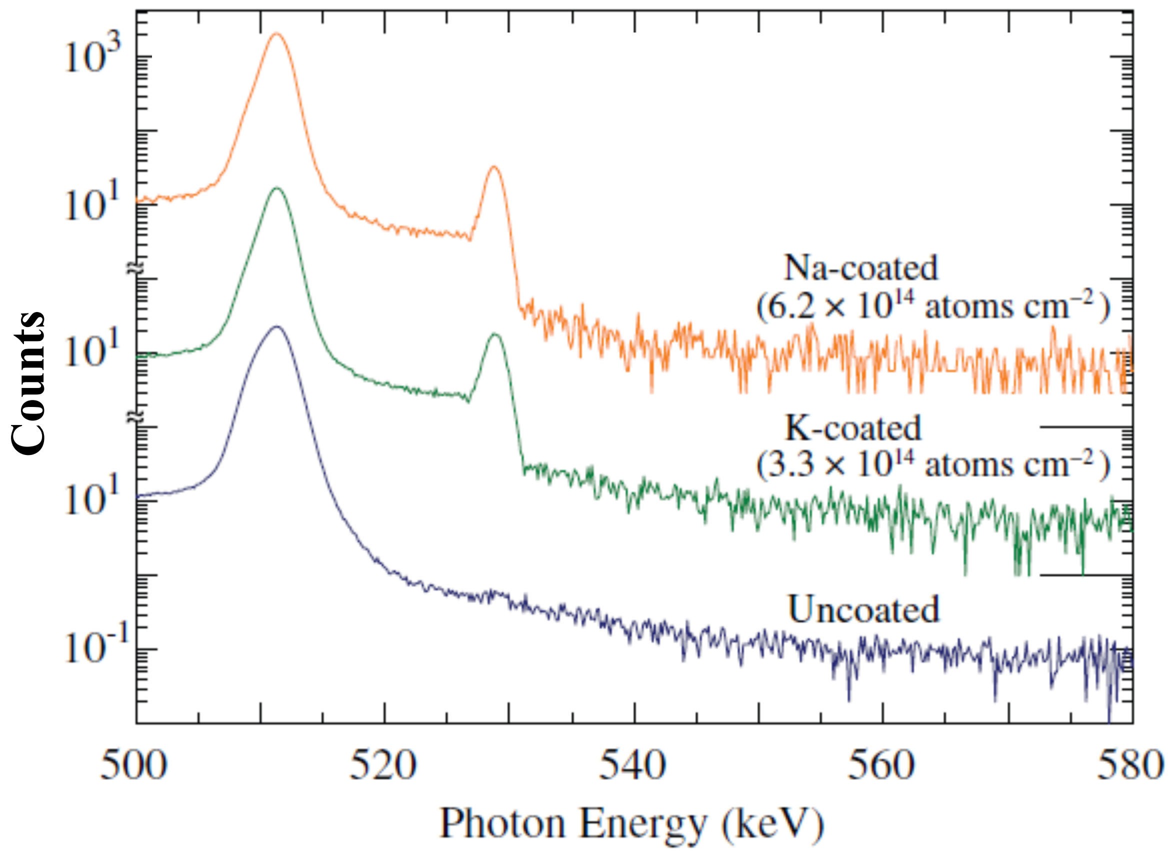


vacuum : 7 x 10^{-8} Pa (5 x 10^{-10} torr)



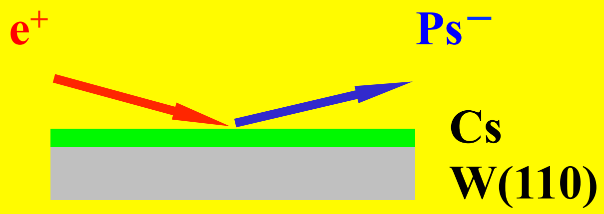
Ps^- emission efficiency was only 0.007%.
(1/4 of that of beam-foil method)

Effect of alkali metal coating for the Ps⁻ emission



Terabe, Michishio, Tachibana and Nagashima, New J. Phys. 14 (2012) 015003

Suggestion for Ps^- formation using Cs coated surface :



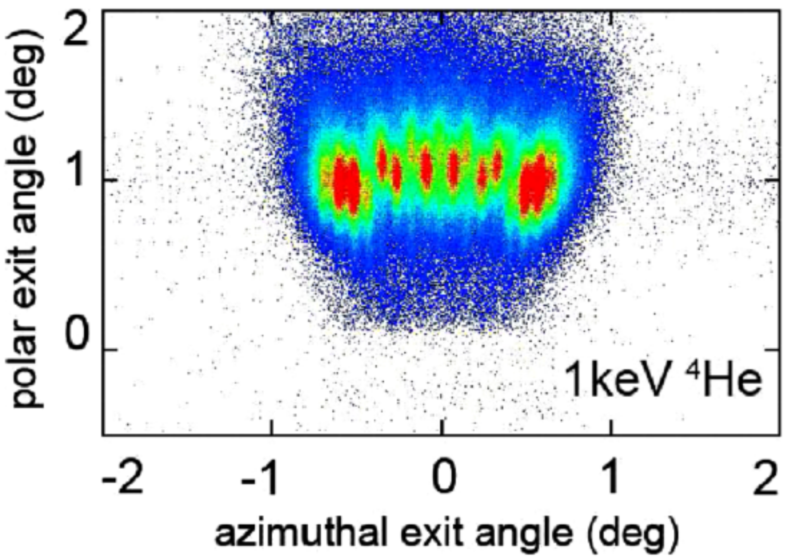
"at grazing angles, good yields of monoenergetic Ps^- might be obtained at positron incident energies of a few eV and might result in a well-collimated tunable Ps beam with a small energy spread."

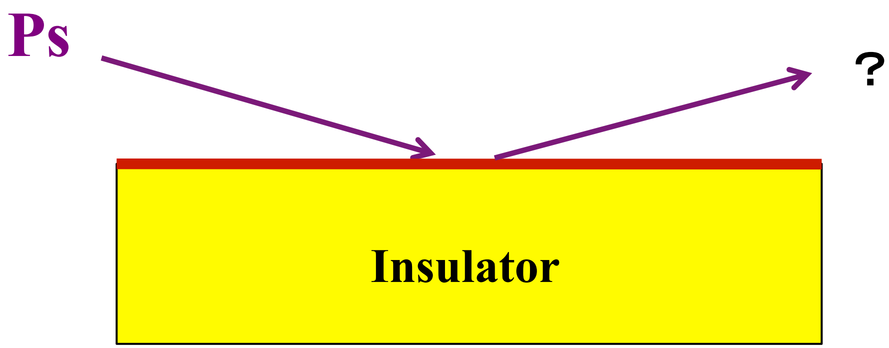
(G. Laricchia, "Positron Spectroscopy of Solids", (1995) 401)

Application of the energy tunable Ps beam (future plan)

2. Grazing Incidence Fast Ps Diffraction (GIFPsD)
or Reflected High Energy Ps Diffraction (RHEPsD)

Fast Atom Diffraction at Surfaces





Schűller et al., Phys. Rev. Lett. 98 (2007) 016103
Rousseau et. al., Phys. Rev. Lett. 98 (2007) 016104