TASCA 16

15th Workshop on
Recoil Separator for Superheavy Element Chemistry

Measurements of the first ionization potentials of the heaviest actinides

T. K. Sato

Advanced Science Research Center

Japan Atomic Energy Agency

Collaboration

M. Asai
N. Sato
Y. Kaneya
K. Tsukada
A. Toyoshima
M. Schädel
Y. Nagame
A. Mitsukai

A. Vascon
H. Makii
S. Takeda
M. Sakama
D. Sato
K. Ooe
S. Miyashita

T. Stora
A. Osa
S. Ichikawa
A. Borschevsky
E. Eliav
U. Kaldor
R. Eichler
V. Pershina

J. Grund
D. Renisch
Ch. E. Düllmann
J. V. Kratz
K. Eberhardt
P. Thörle-Pospiech
J. Runke
N. Trautmann

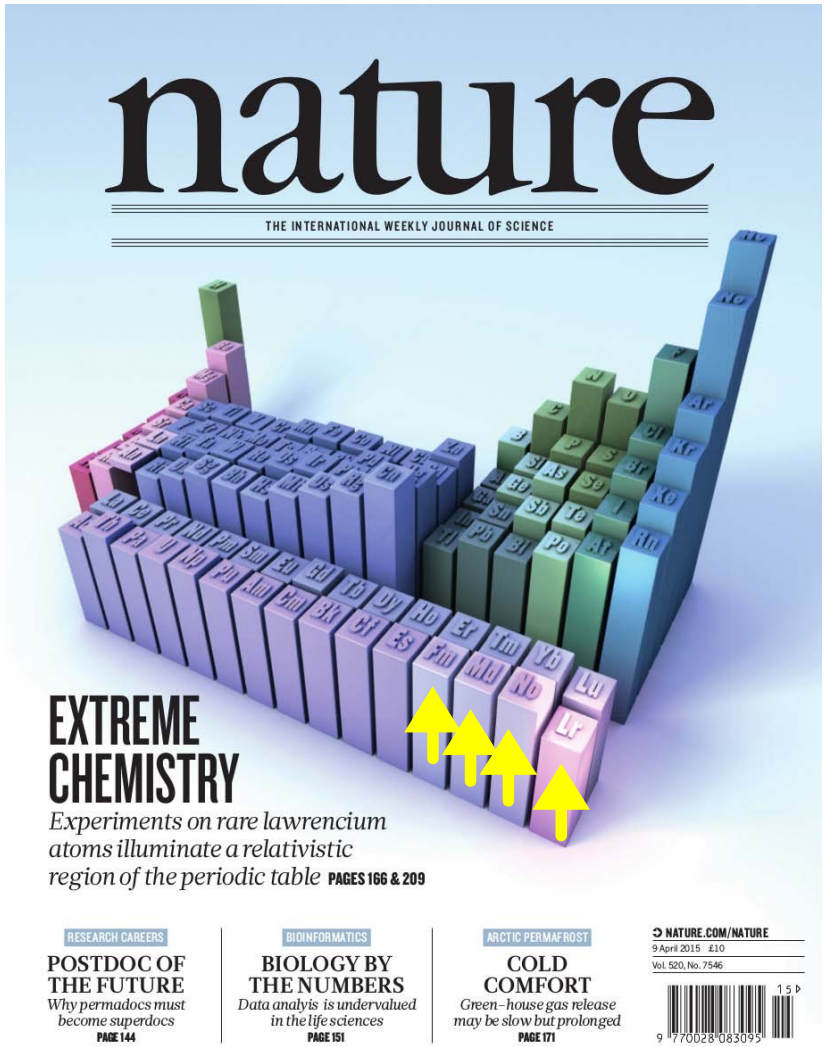
Contents

1) Measurements of the first ionization potential (IP_1) of the heavy actinides at JAEA

2) Recent activities at JAEA

- Adsorption behavior of lawrencium (Lr, Z=103) on Ta surface

IP_1 measurements of heavy elements



LETTER

doi:10.1038/nature14342

Measurement of the first ionization potential of lawrencium, element 103

T. K. Sato[1], M. Asai[1], A. Borschevsky[2,3], T. Stora[4], N. Sato[1], Y. Kaneya[1,5], K. Tsukada[1], Ch. E. Düllmann[3,6,7], K. Eberhardt[3,7], E. Eliav[8], S. Ichikawa[1,9], U. Kaldor[8], J. V. Kratz[7], S. Miyashita[10], Y. Nagame[1,5], K. Ooe[11], A. Osa[1], D. Renisch[7], J. Runke[6], M. Schädel[1], P. Thörle-Pospiech[3,7], A. Toyoshima[1] & N. Trautmann[7]

The chemical properties of an element are primarily governed by the configuration of electrons in the valence shell. Relativistic effects influence the electronic struct... of the periodic table, and the... seventh row—including the ... configurations[1,2]. Atomic s a... ivistic effects, whereas $p_{3/2}$, d... ground-state configurations ... of lighter elements in the sam... (IP_1) is a measu... spallation reaction of uranium[14]. IP_1 values of heavy elements with $Z \geq 100$, however, could not be determined experimentally, because

T. K. Sato *et al.*
***Nature* 520 (Apr.9) (2015) 209-211.**

Electronic configuration of heavy elements influenced by strong rel. eff.

Experimental determination of the first ionization potential (IP_1)

Surface ionization

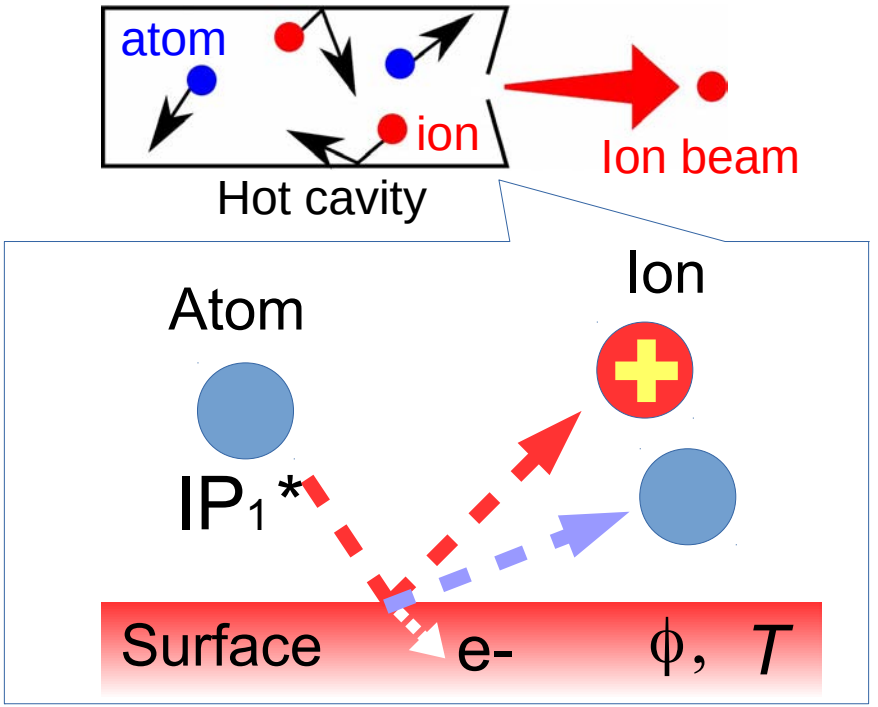
Low production rate and/or short half-lives

A NEW IP_1 measurement method based on surface ionization process

Surface ionization

Low production rate and/or short half-lives

A NEW IP_1 measurement method based on surface ionization process



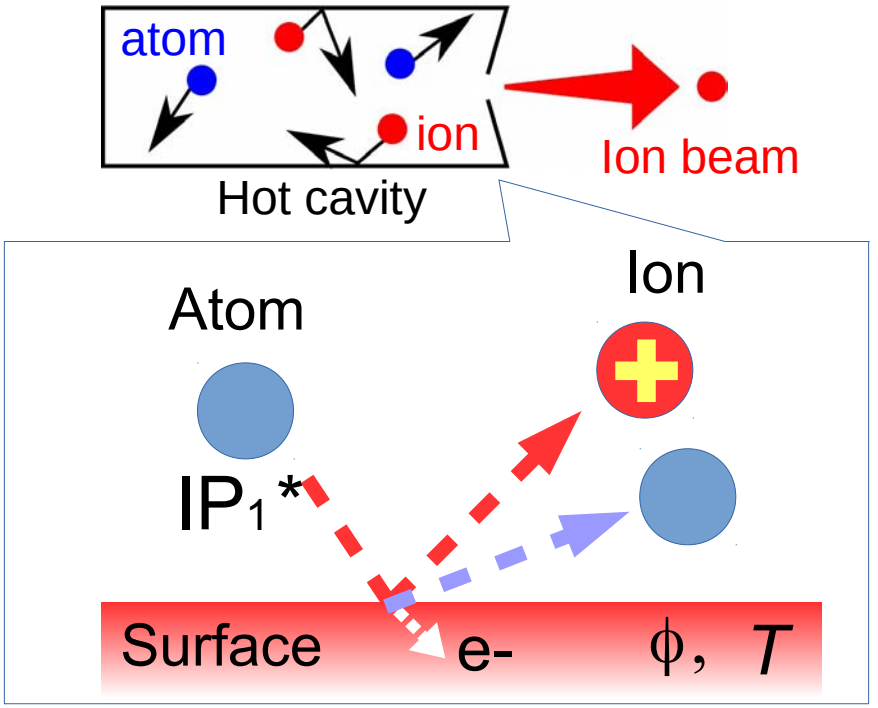
Surface ionization

Saha-Langmuir eq.

$$I_{\text{eff}} = \frac{N \exp\left((\phi - \text{IP}_1^*)/kT\right)}{1 + N \exp\left((\phi - \text{IP}_1^*)/kT\right)}$$

Effective $IP_1(IP_1^*)$: $\text{IP}_1^* = \text{IP}_1 - kT \ln\left(Q_i/Q_o\right)$

I_{eff} : ionization efficiency
φ : work function [eV]
T: surface temperature [K]
Q_i and Q_o: partition functions of ion and atom
IP_1 : The first ionization potential



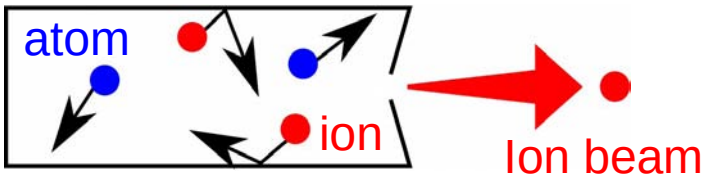
Surface ionization

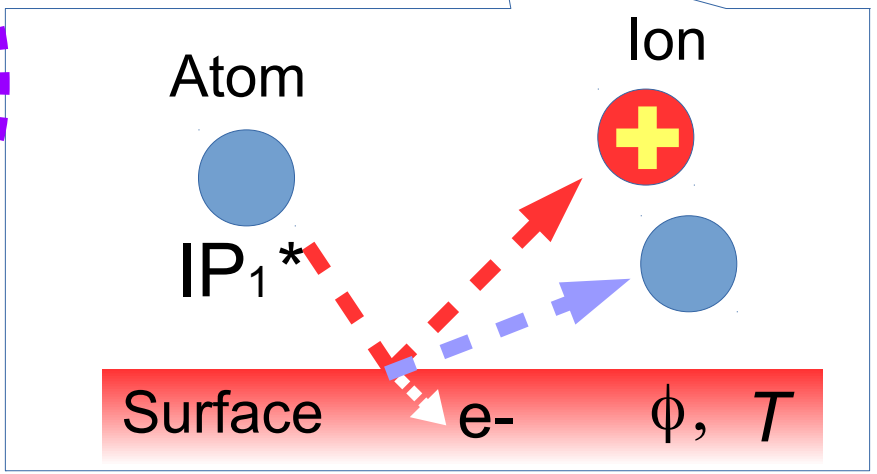
Saha-Langmuir eq.

$$I_{\text{eff}} = \frac{N \exp\left((\phi - \mathrm{IP}_1^*)/kT\right)}{1 + N \exp\left((\phi - \mathrm{IP}_1^*)/kT\right)}$$

Effective $IP_1(IP_1^*)$: $IP_1^* = IP_1 - kT \ln(Q_i/Q_o)$

I_{eff} : ionization efficiency
φ : work function [eV]
T: surface temperature [K]
Q_i and Q_o: partition functions of ion and atom
IP_1 : The first ionization potential





Ionization eff. (I_{eff}) → Effective IP_1 (IP_1^*)

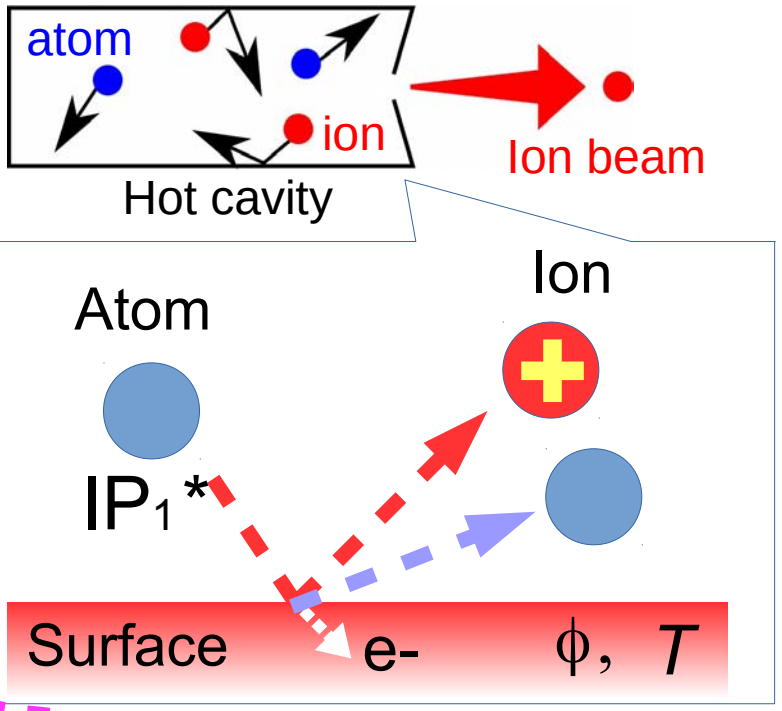
Surface ionization

Saha-Langmuir eq.

$$I_{\text{eff}} = \frac{N \exp\left((\phi - \mathrm{IP}_1^*)/kT\right)}{1 + N \exp\left((\phi - \mathrm{IP}_1^*)/kT\right)}$$

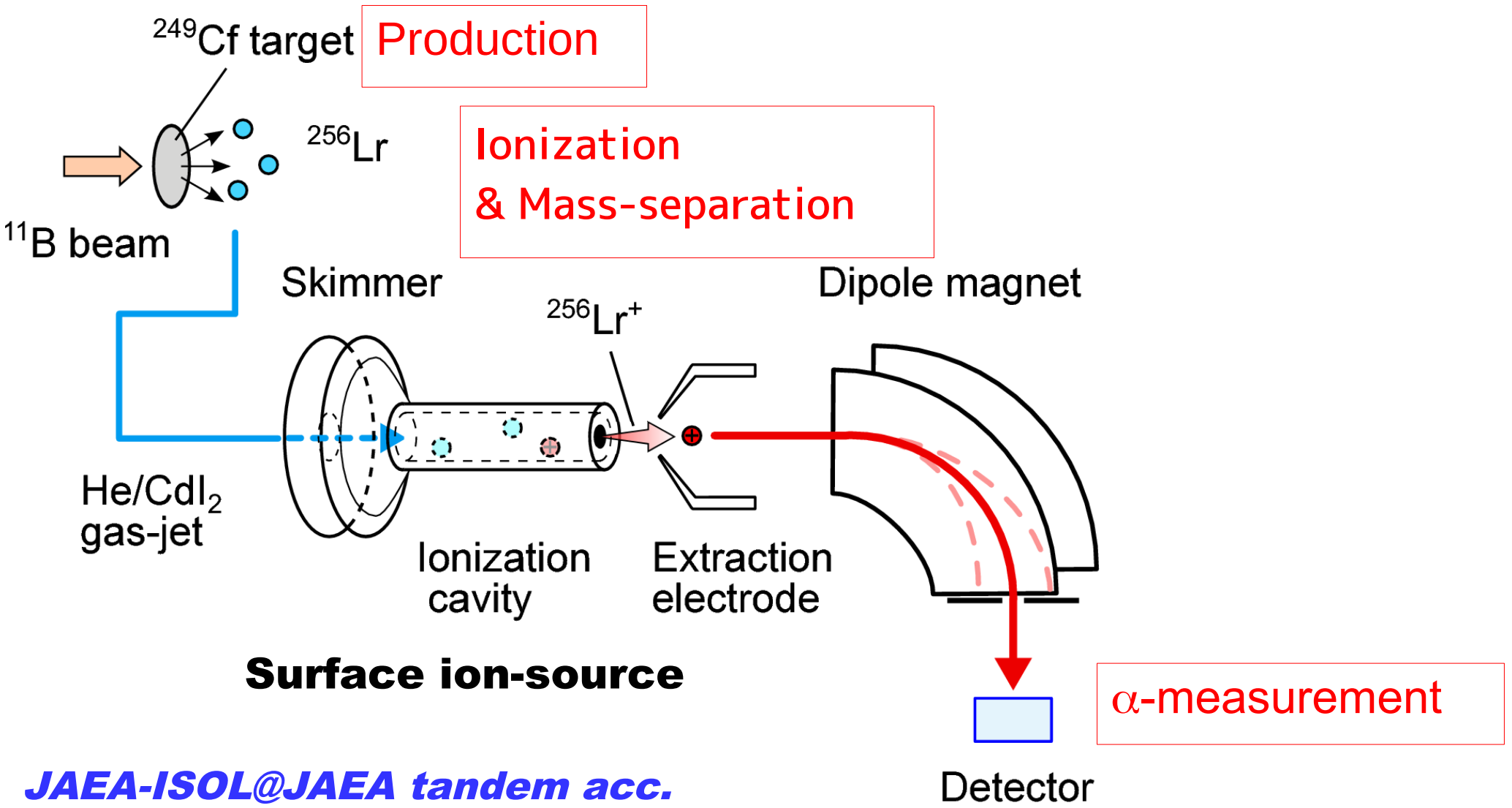
Effective $IP_1(IP_1^*)$: $IP_1^* = IP_1 - kT \ln(Q_i/Q_o)$

I_{eff} : ionization efficiency
φ : work function [eV]
T: surface temperature [K]
Q_i and Q_o: partition functions of ion and atom
IP_1 : The first ionization potential



Ionization eff. (I_{eff}) → **Effective IP_1 (IP_1^*)** → **IP_1**

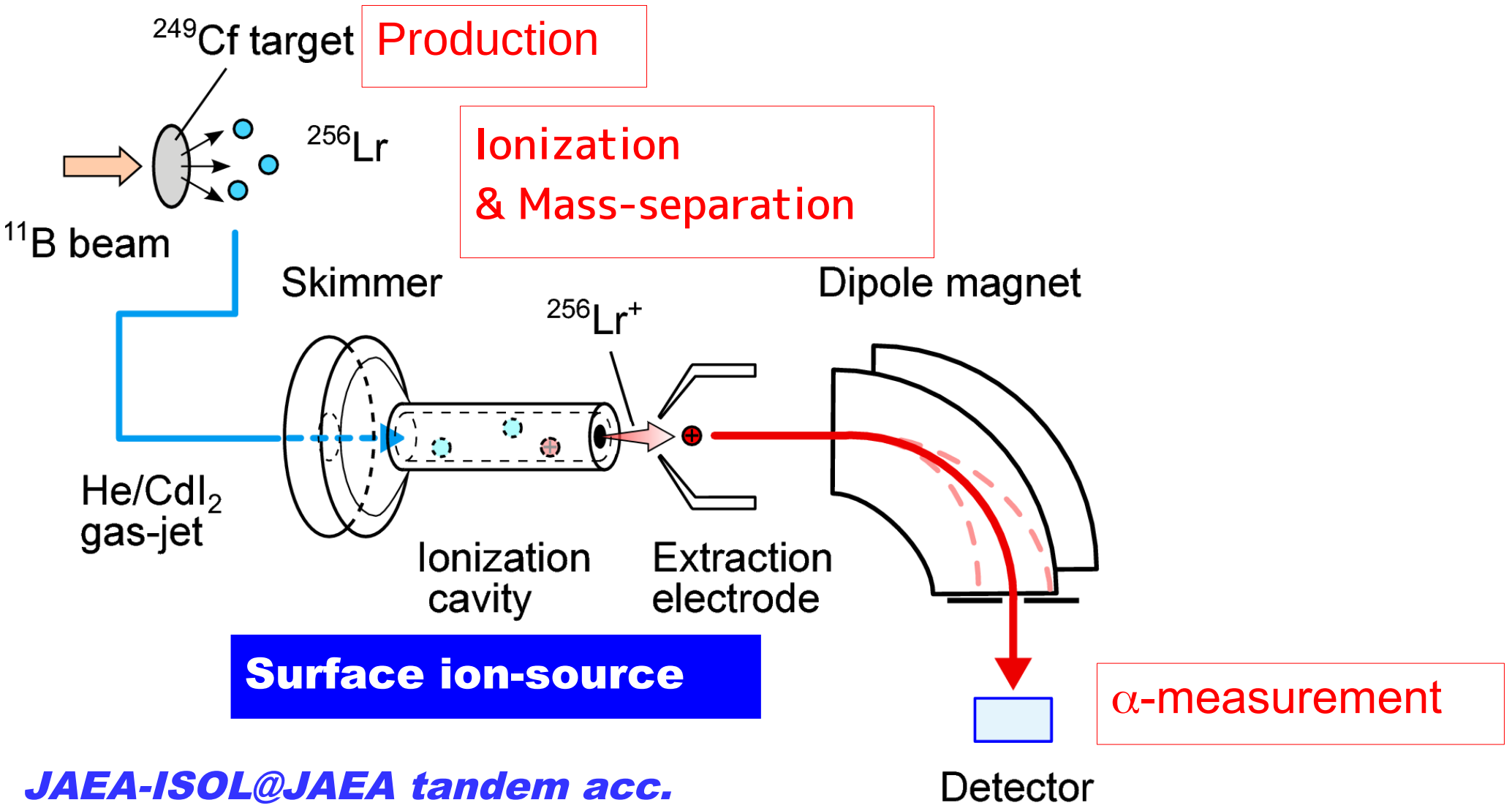
Experimental setup



JAEA-ISOL@JAEA tandem acc.

[1] T.K.Sato et al JRNC, 303, 1253-1257 (2015).

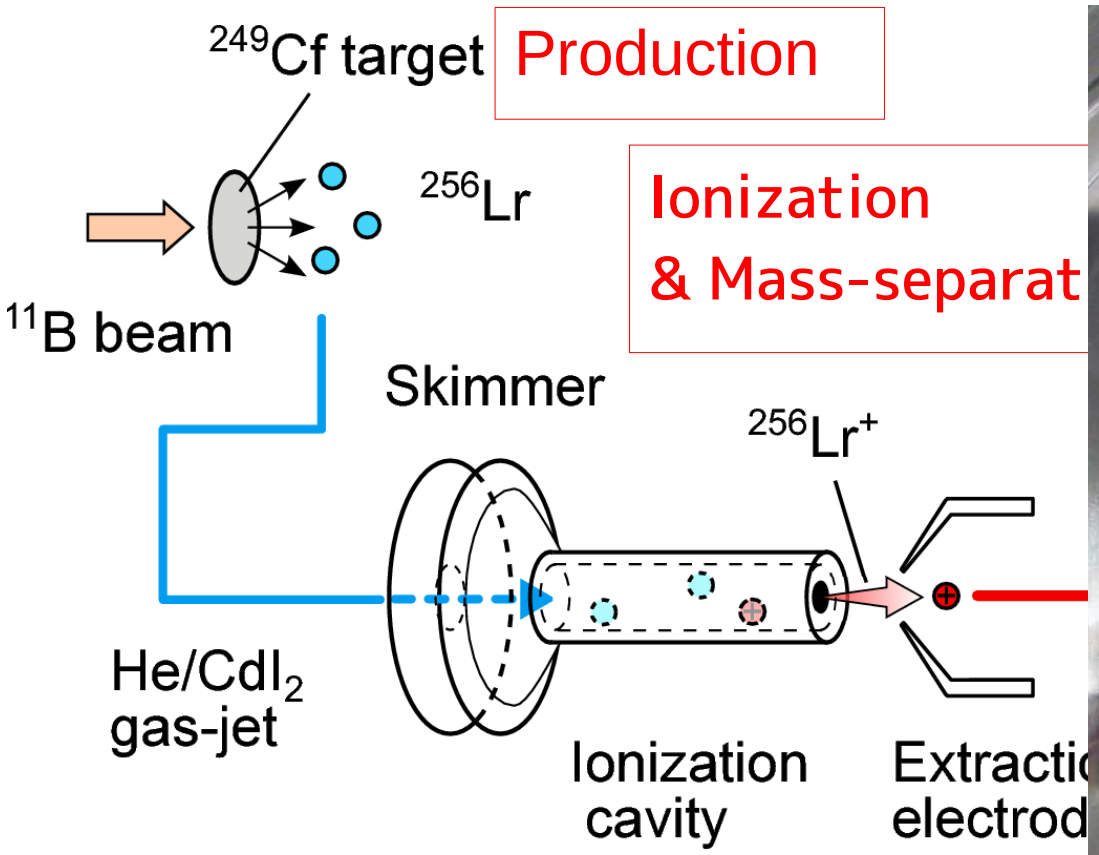
Experimental setup

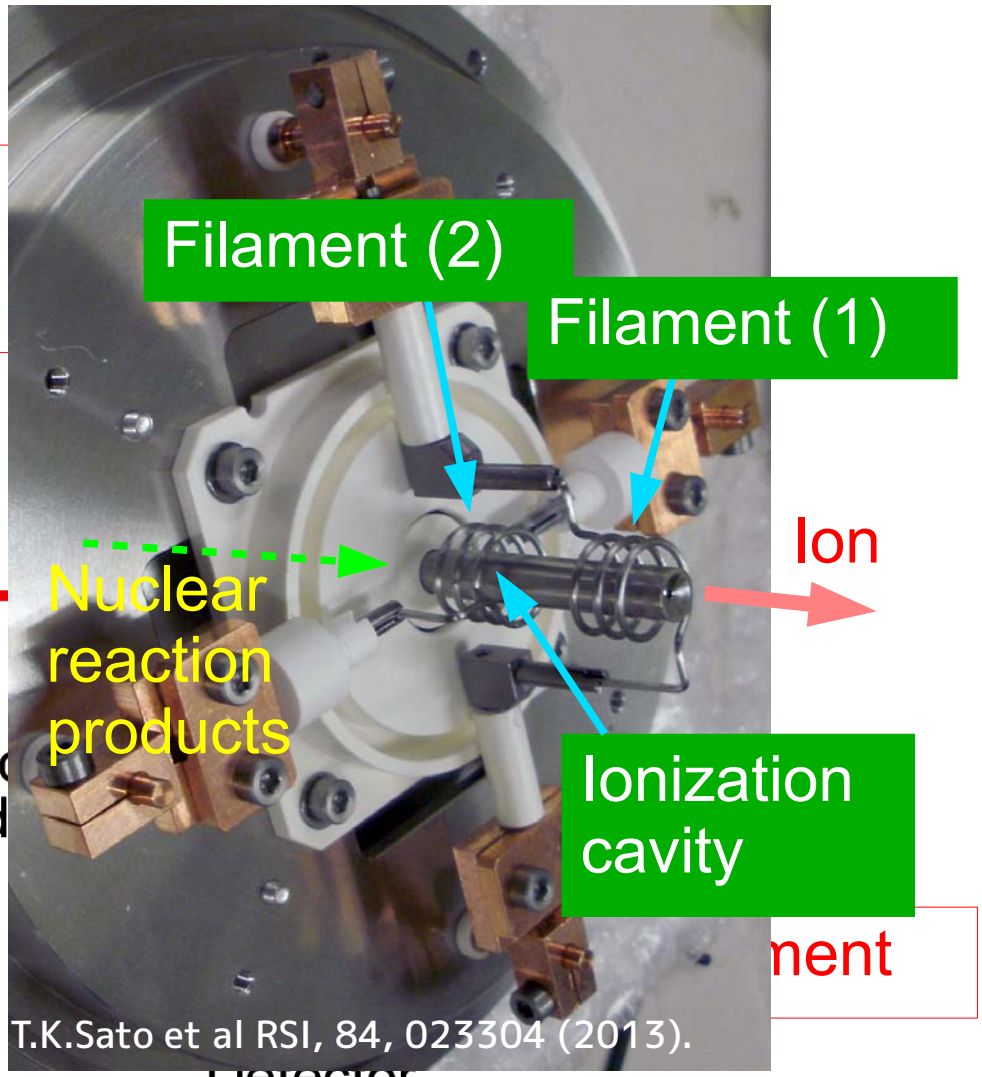


JAEA-ISOL@JAEA tandem acc.

[1] T.K.Sato et al JRNC, 303, 1253-1257 (2015).

Experimental setup





JAEA-ISOL@JAEA tandem acc.

[1] T.K.Sato et al JRNC, 303, 1253-1257 (2015).

IP_1 measurement of Lr

Isotopes : ^{80}Rb, ^{142,143}Eu, ^{143}Sm,
^{148}Tb,^{153,154}Ho, ^{157}Er,
^{162}Tm, ^{165}Yb, & ^{168}Lu

Beam : ^{11}B(67.9 MeV)

Targets : ^{136}Ce,^{141}Pr,^{142}Nd,^{147}Sm,
Eu, ^{156}Gd, ^{159}Tb,
^{162}Dy, and Ge

Ionization temp.: 2700K

S-L eq.

$$I_{\text{eff}} = \frac{N \exp\left((\phi - \text{IP}_1^*)/kT\right)}{1 + N \exp\left((\phi - \text{IP}_1^*)/kT\right)}$$

in the present system

IP_1 measurement of Lr

Isotopes : ^{80}Rb, ^{142,143}Eu, ^{143}Sm, ^{148}Tb, ^{153,154}Ho, ^{157}Er, ^{162}Tm, ^{165}Yb, & ^{168}Lu

Beam : ^{11}B(67.9 MeV)

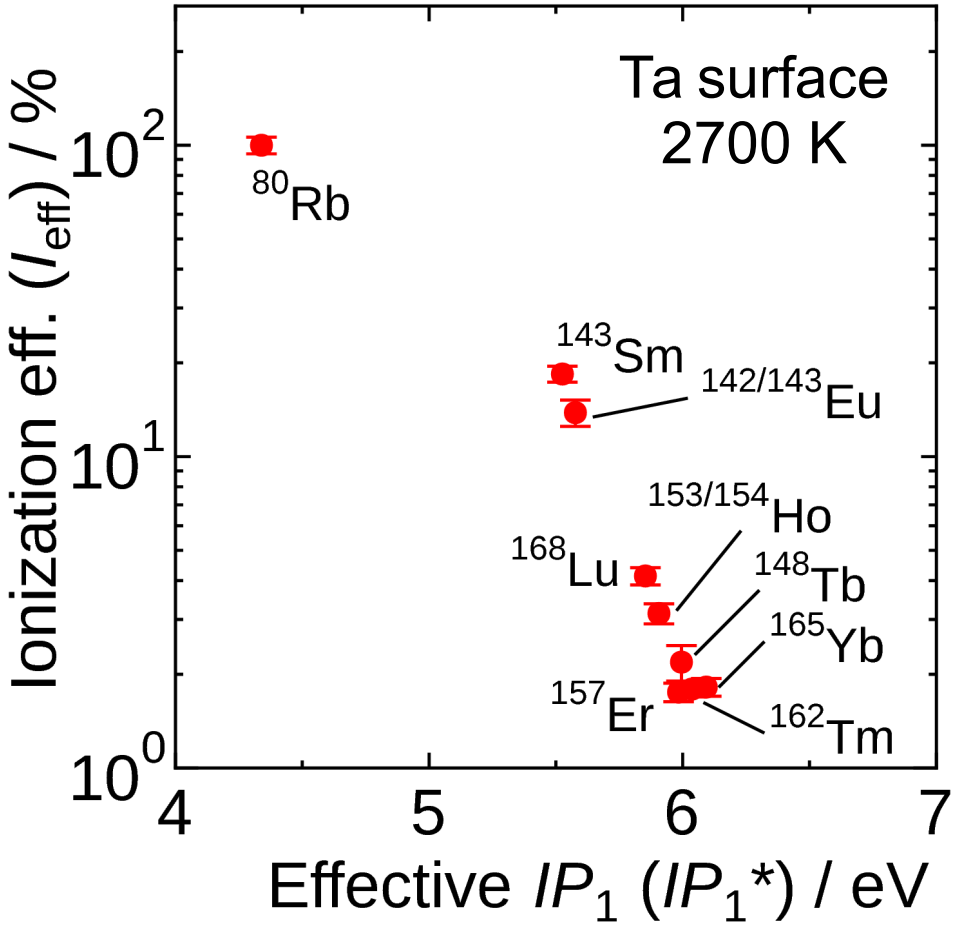
Targets : ^{136}Ce, ^{141}Pr, ^{142}Nd, ^{147}Sm, Eu, ^{156}Gd, ^{159}Tb, ^{162}Dy, and Ge

Ionization temp.: 2700K

S-L eq.

$$I_{\mathrm{eff}} = \frac{N \exp\left((\phi - \mathrm{IP}_1^*)/kT\right)}{1 + N \exp\left((\phi - \mathrm{IP}_1^*)/kT\right)}$$

in the present system



IP_1 measurement of Lr

Isotopes : ^{80}Rb, ^{142,143}Eu, ^{143}Sm, ^{148}Tb, ^{153,154}Ho, ^{157}Er, ^{162}Tm, ^{165}Yb, & ^{168}Lu

Beam : ^{11}B(67.9 MeV)

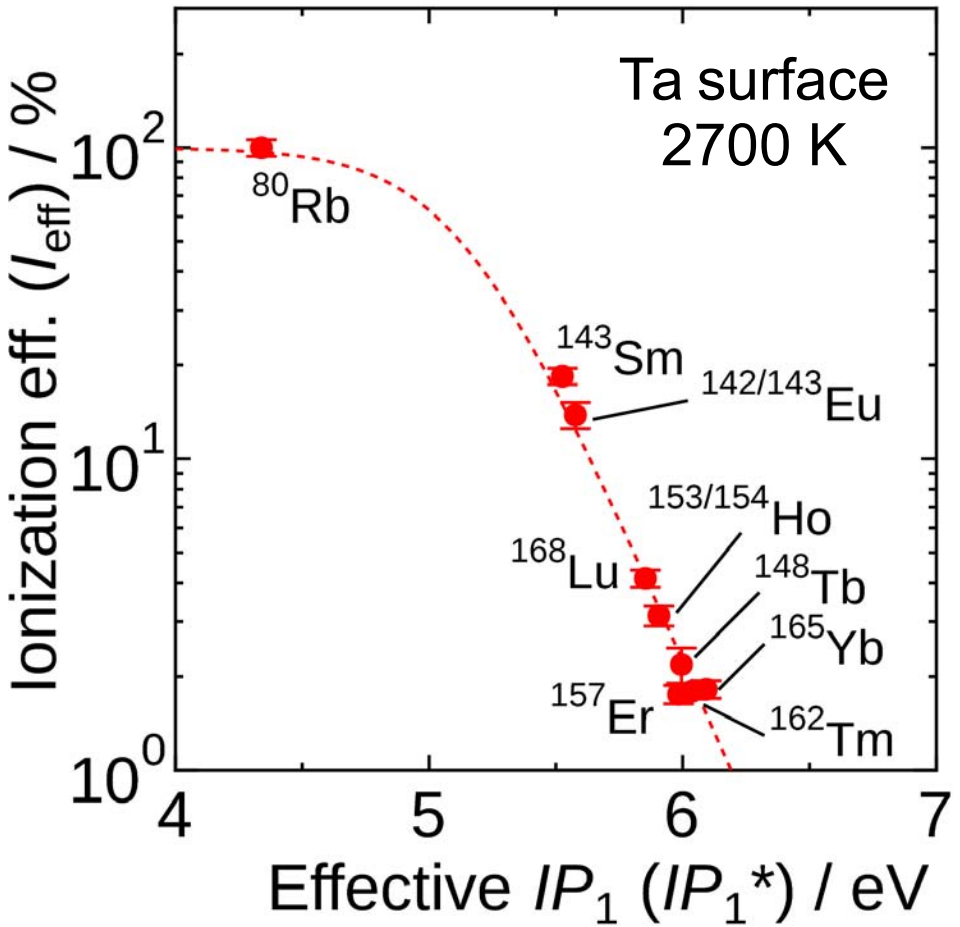
Targets : ^{136}Ce, ^{141}Pr, ^{142}Nd, ^{147}Sm, Eu, ^{156}Gd, ^{159}Tb, ^{162}Dy, and Ge

Ionization temp.: 2700K

S-L eq.

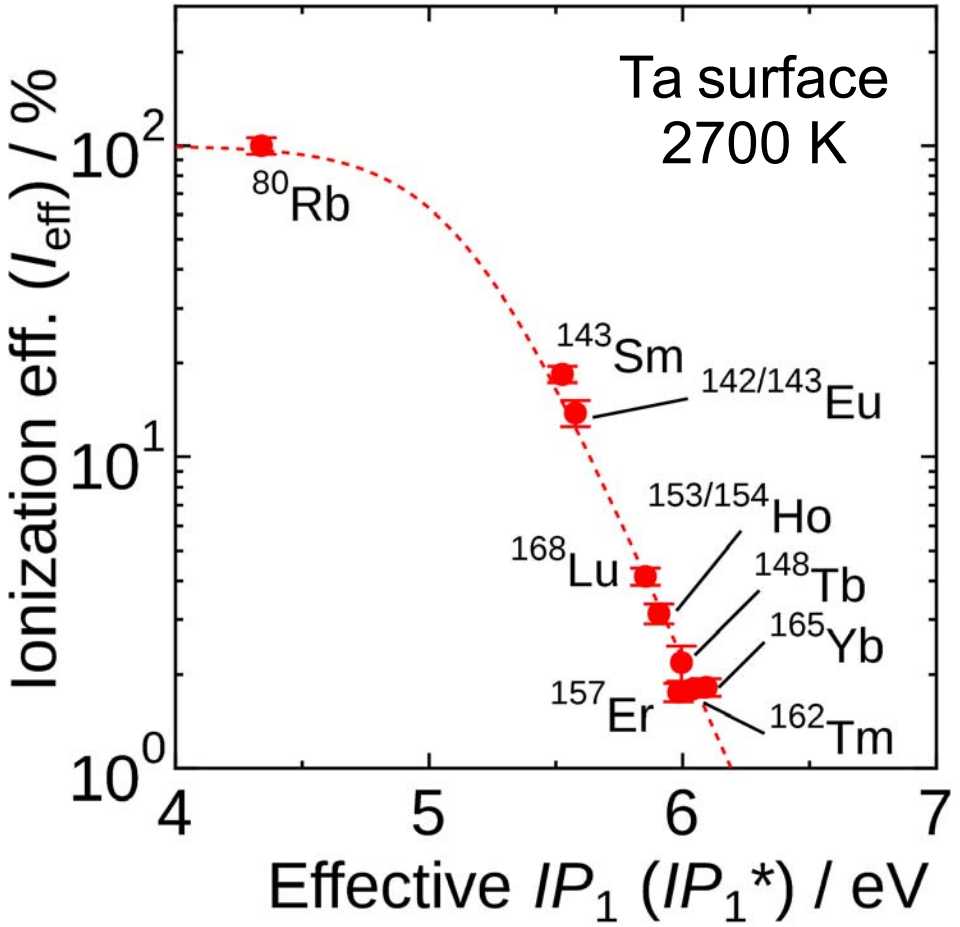
$$I_{\mathrm{eff}} = \frac{N \exp\left((\phi - \mathrm{IP}_1^*)/kT\right)}{1 + N \exp\left((\phi - \mathrm{IP}_1^*)/kT\right)}$$

in the present system



IP_1 measurement of Lr

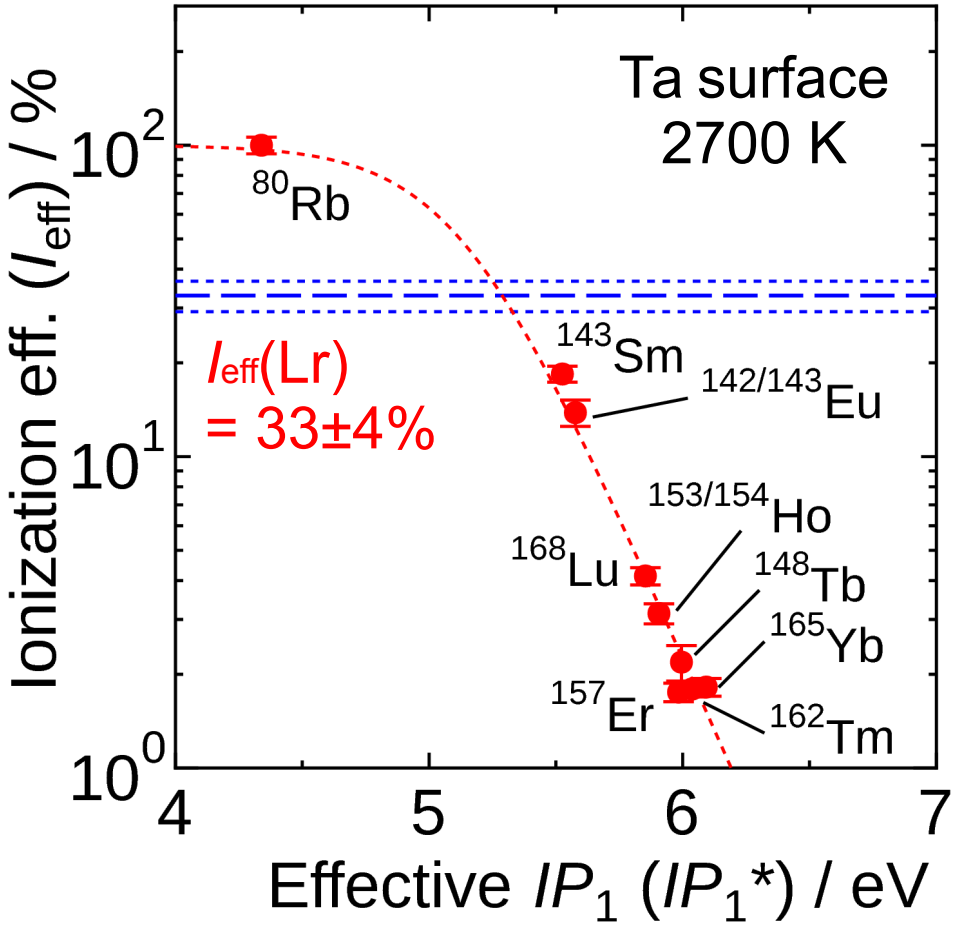
Isotope: ^{256}Lr ($T_{1/2}$ = 27 s)
Beam : ^{11}B (67.9 MeV)
Target : ^{249}Cf (260 μg/cm^2)
Ionization temp.: 2700K



IP_1 measurement of Lr

Isotope: ^{256}Lr ($T_{1/2}$ = 27 s)
Beam : ^{11}B (67.9 MeV)
Target : ^{249}Cf (260 μg/cm^2)
Ionization temp.: 2700K

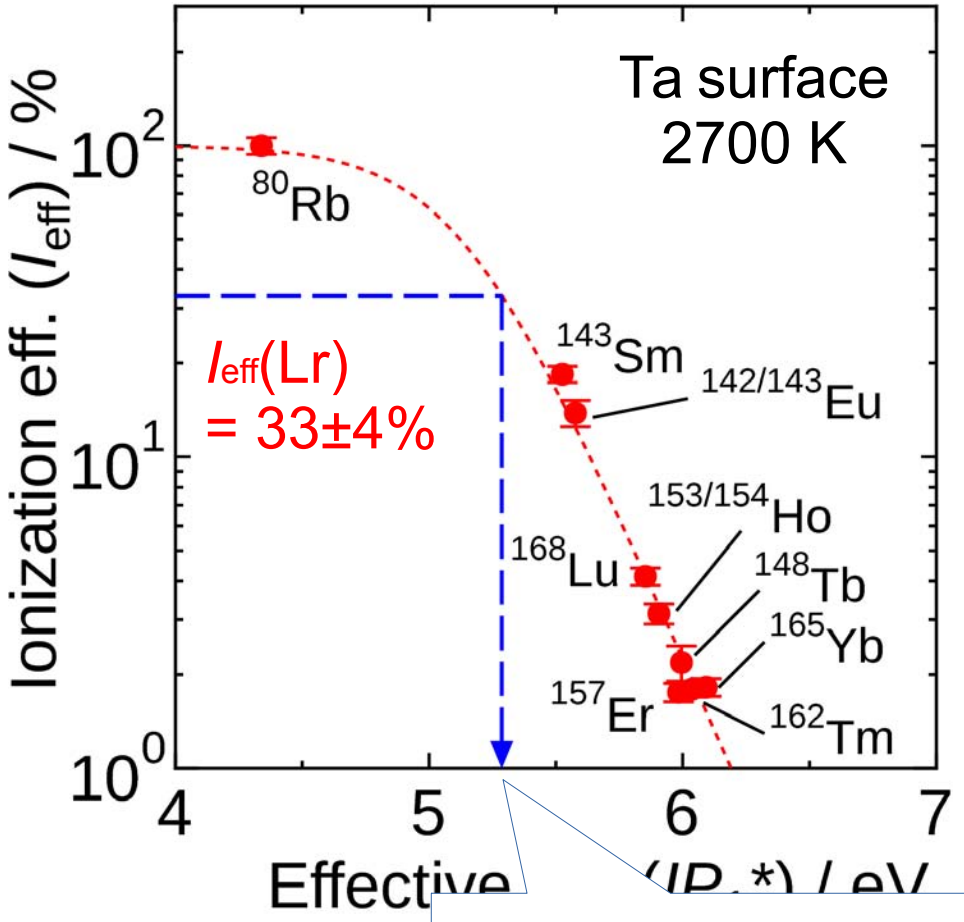
I_{eff}(Lr) = 33 ± 4%
in the present system



IP_1 measurement of Lr

Isotope: ^{256}Lr ($T_{1/2}$ = 27 s)
Beam : ^{11}B (67.9 MeV)
Target : ^{249}Cf (260 μg/cm^2)
Ionization temp.: 2700K

I_{eff}(Lr) = 33 ± 4%
in the present system

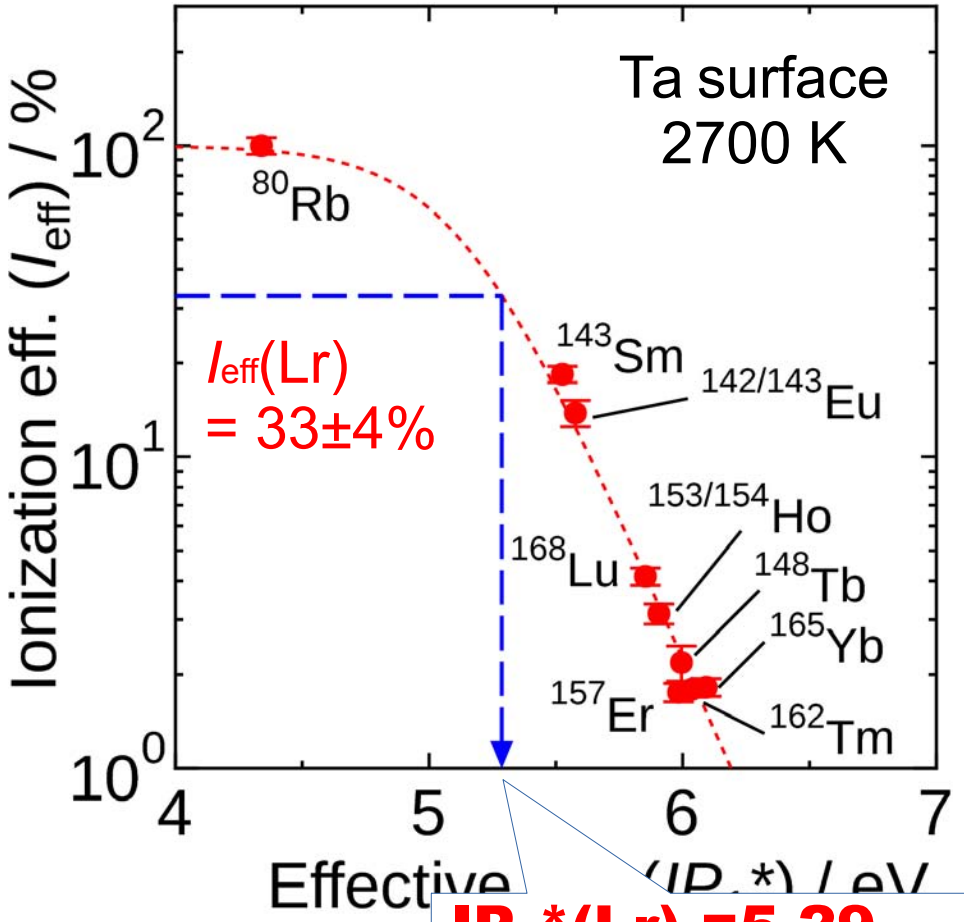


IP_1*(Lr) =5.29

IP_1 measurement of Lr

Isotope: ^{256}Lr ($T_{1/2}$ = 27 s)
Beam : ^{11}B (67.9 MeV)
Target : ^{249}Cf (260 μg/cm^2)
Ionization temp.: 2700K

I_{eff}(Lr) = 33 ± 4%
in the present system



IP_1*(Lr) =5.29

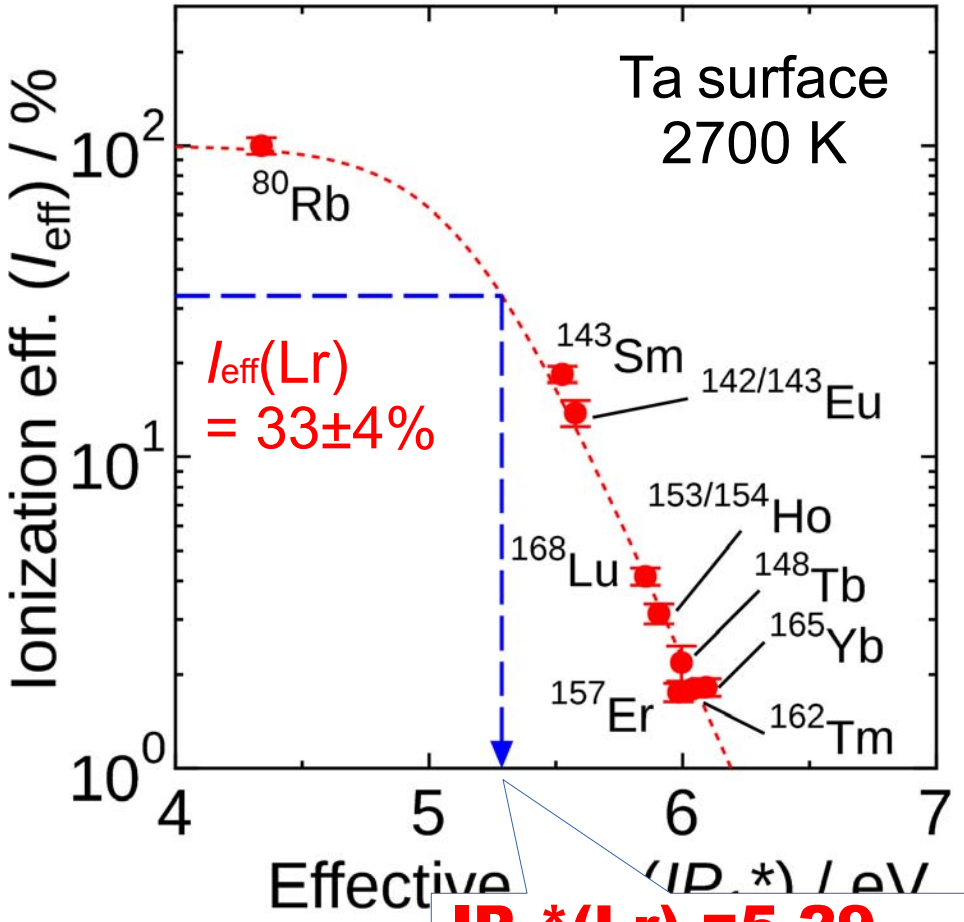
IP_1(Lr) = 4.96

IP_1 measurement of Lr

Isotope: ^{256}Lr ($T_{1/2}$ = 27 s)
Beam : ^{11}B (67.9 MeV)
Target : ^{249}Cf (260 μg/cm^2)
Ionization temp.: 2700K

I_{eff}(Lr) = 33 ± 4%
in the present system

IP_1(Lr) = 4.96±0.08 eV



IP_1*(Lr) =5.29

IP_1(Lr) = 4.96

IP_1 measurement of heavy actinides

^{257}No ($T_{1/2}$ = 24.5 s) : ^{248}Cm(^{13}C, 4n)

^{251}Md ($T_{1/2}$ = 4.27 min) : ^{243}Am (^{12}C, 4n)

^{249}Fm ($T_{1/2}$ = 2.6 min) : ^{243}Am (^{11}B, 5n)

IP_1 measurement of heavy actinides

^{257}No ($T_{1/2}$ = 24.5 s) : ^{248}Cm(^{13}C, 4n)

^{251}Md ($T_{1/2}$ = 4.27 min) : ^{243}Am (^{12}C, 4n)

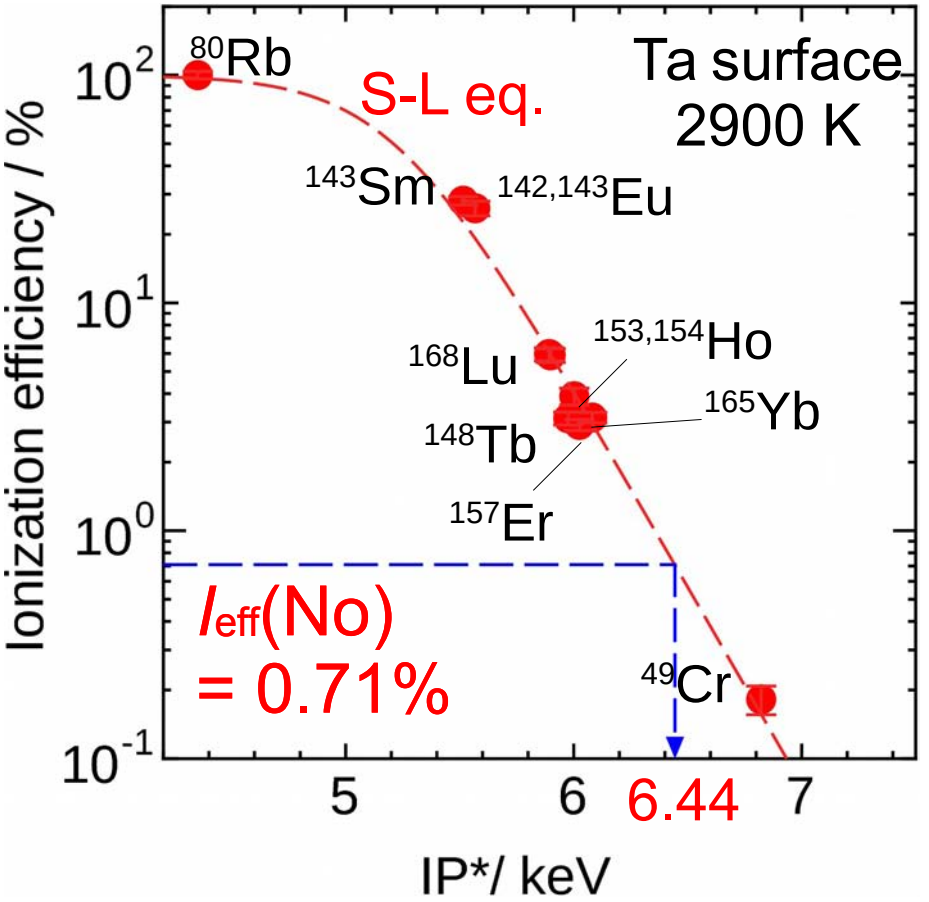
^{249}Fm ($T_{1/2}$ = 2.6 min) : ^{243}Am (^{11}B, 5n)

ex)

I_{eff}(No) = 0.71 ± 0.06 %

IP_1(No) = 6.63 ± 0.08 eV

(Preliminary)



IP_1 measurement of heavy actinides

^{257}No ($T_{1/2}$ = 24.5 s) : ^{248}Cm(^{13}C, 4n)

^{251}Md ($T_{1/2}$ = 4.27 min) : ^{243}Am (^{12}C, 4n)

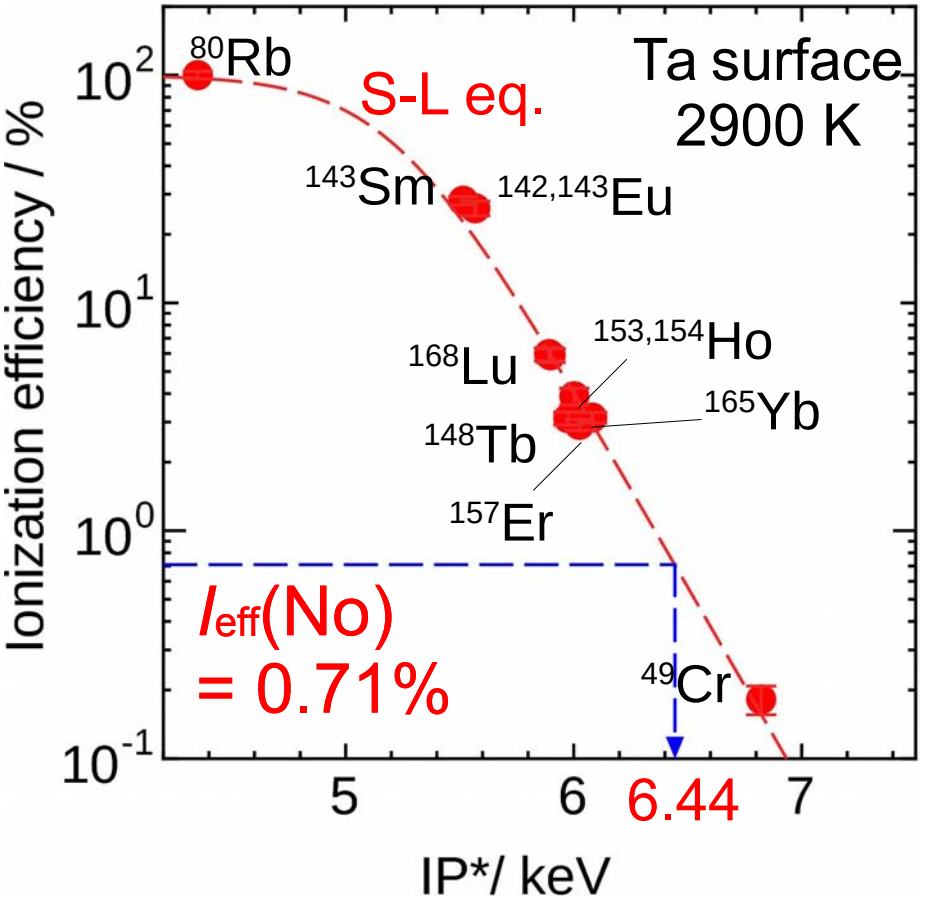
^{249}Fm ($T_{1/2}$ = 2.6 min) : ^{243}Am (^{11}B, 5n)

ex)

I_{eff}(No) = 0.71 ± 0.06 %

IP_1(No) = 6.63 ± 0.08 eV

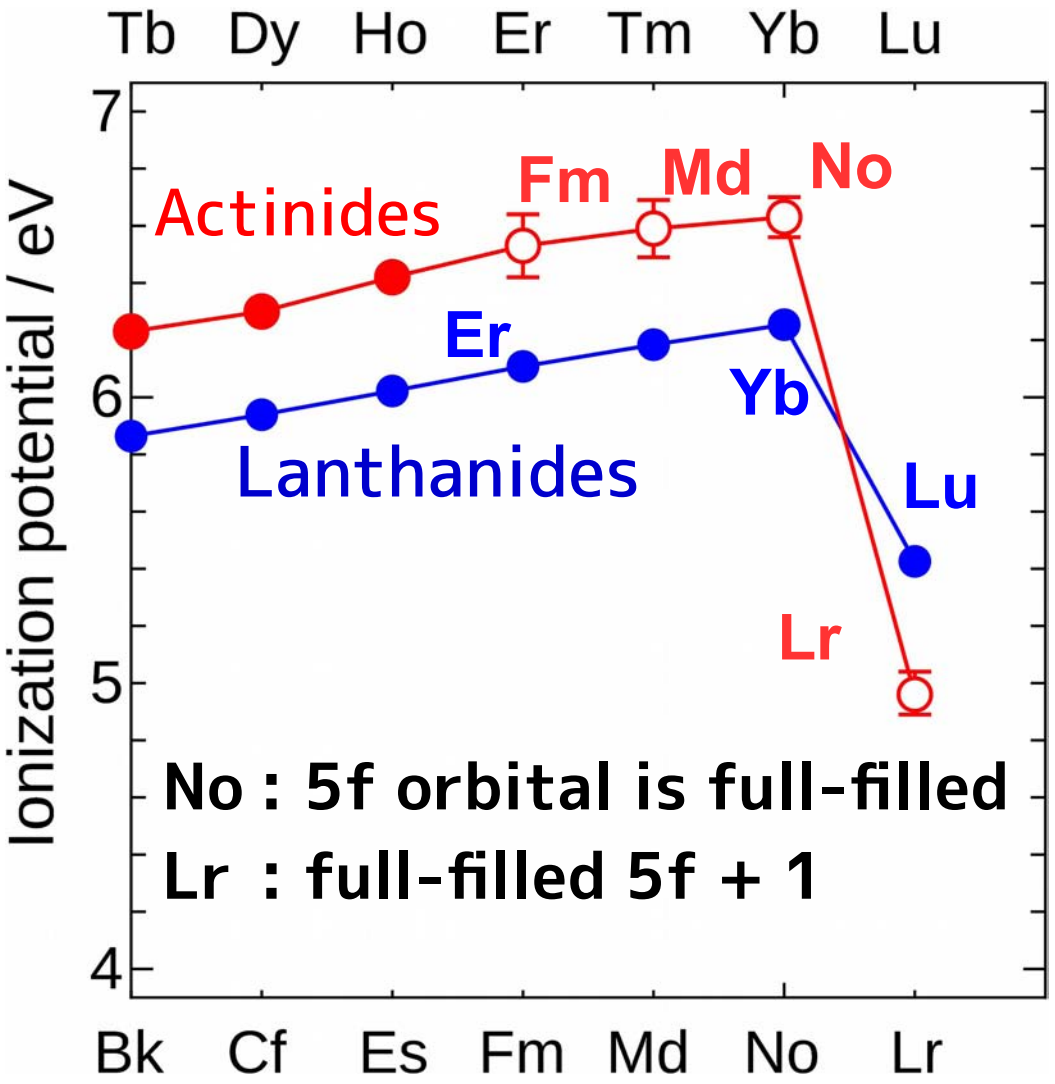
(Preliminary)



	Fm	Md	No
J.Sugar [1]	6.50	6.58	6.65
this work	**6.53 ± 0.11**	**6.59 ± 0.10**	**6.63 ± 0.08**

[1] J. Sugar, J. Chem. Phys. 60 (1974) 4103.

IP_1 measurement of heavy actinides



We successfully measured IP_1 values of Lr ~ Fm using the surface-ionization method.

Lr: $IP_1(Lr) = 4.96 \pm 0.08$ eV

→ **Lr: [Rn]$5f^{14}7s^2 7p_{1/2}$**

↔ Lu : [Xe]$4f^{14}6s^2 5d$

No: $IP_1(No) = 6.63 \pm 0.08$ eV

→ **full-filled 5f orbitals**

Fm → No → Lr

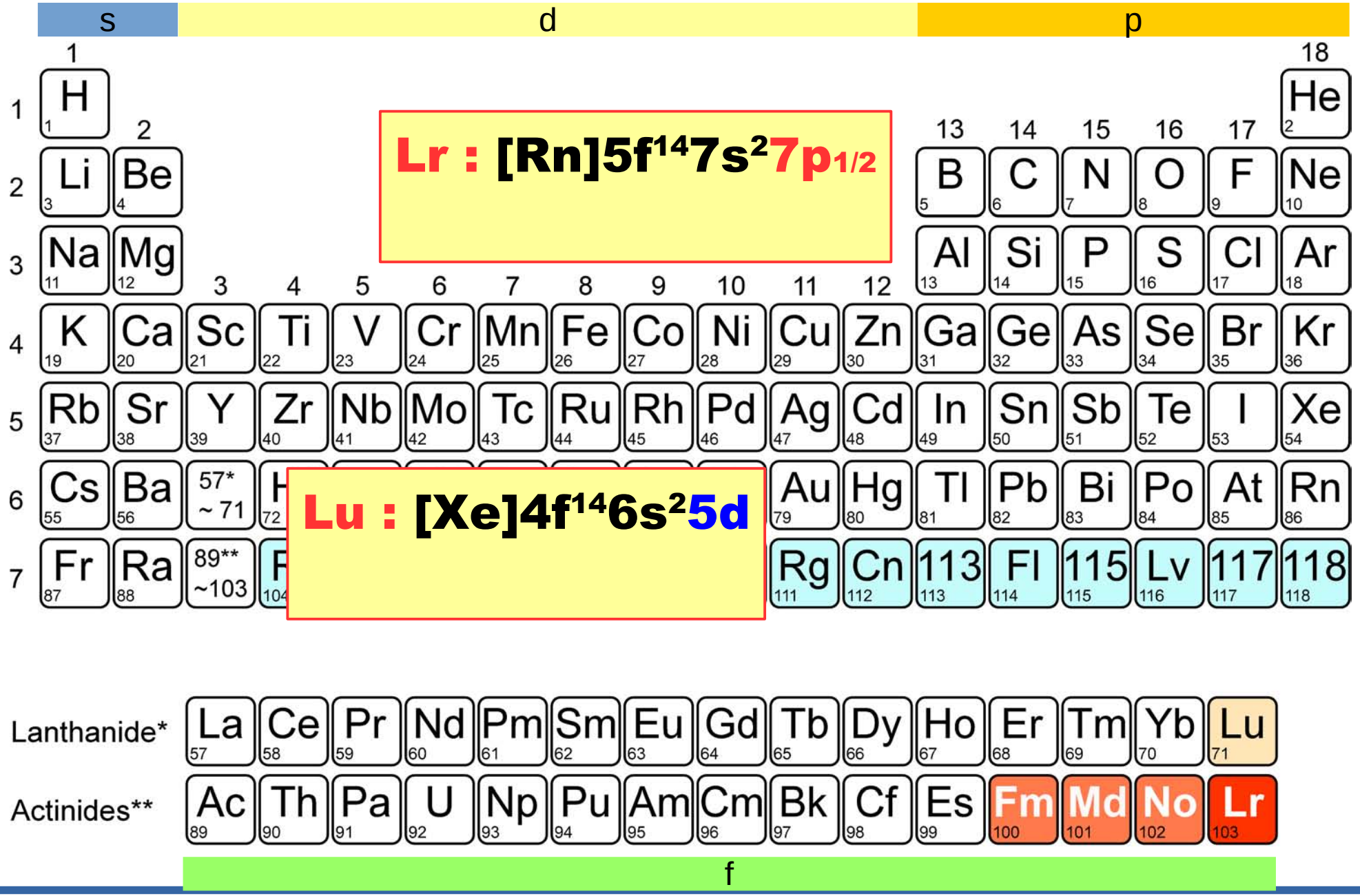
Similar to Er → Yb → Lu

Actinide series would be terminated with Lr.

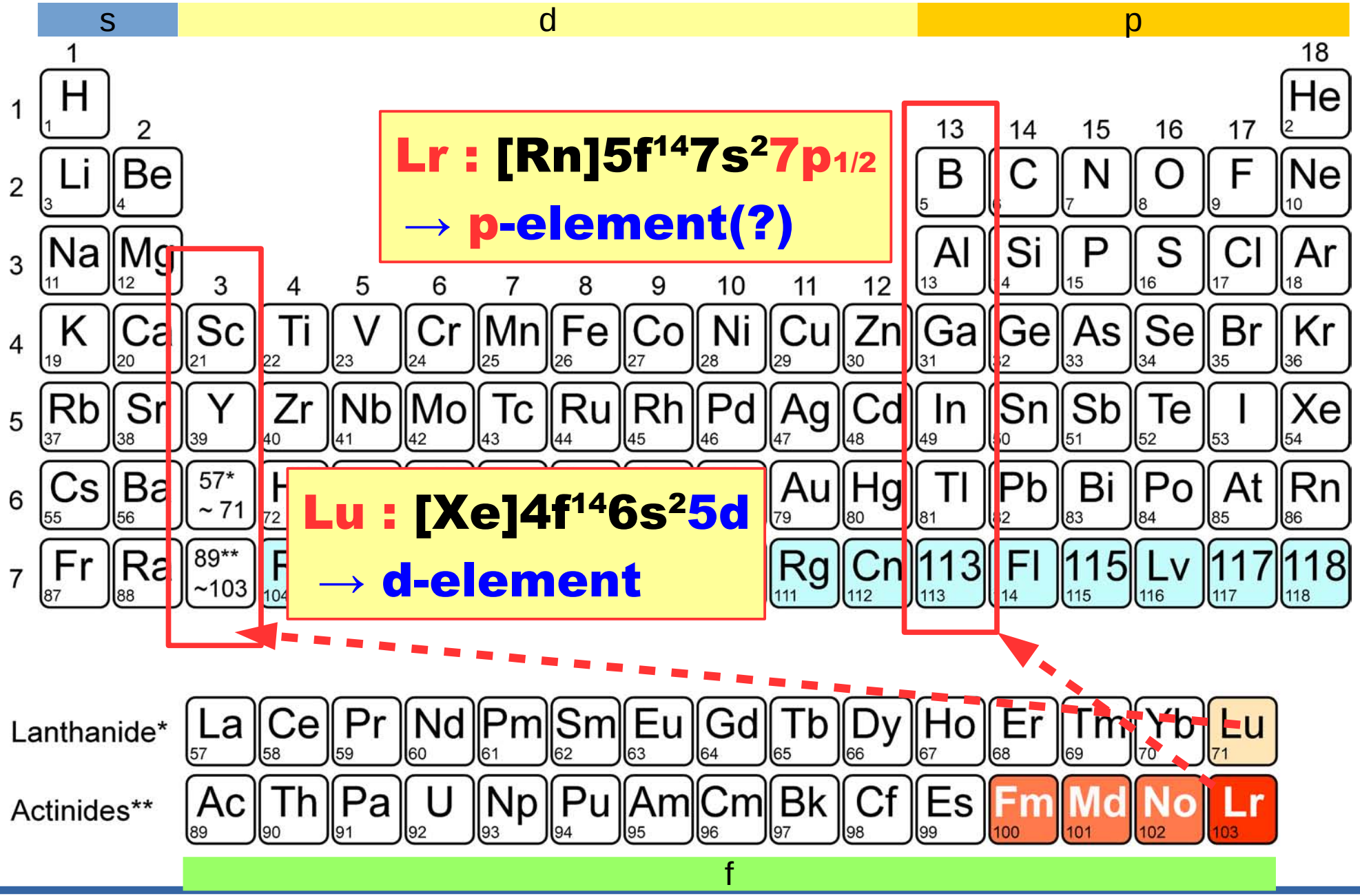
Present status

Adsorption behavior of Lr on Ta surface

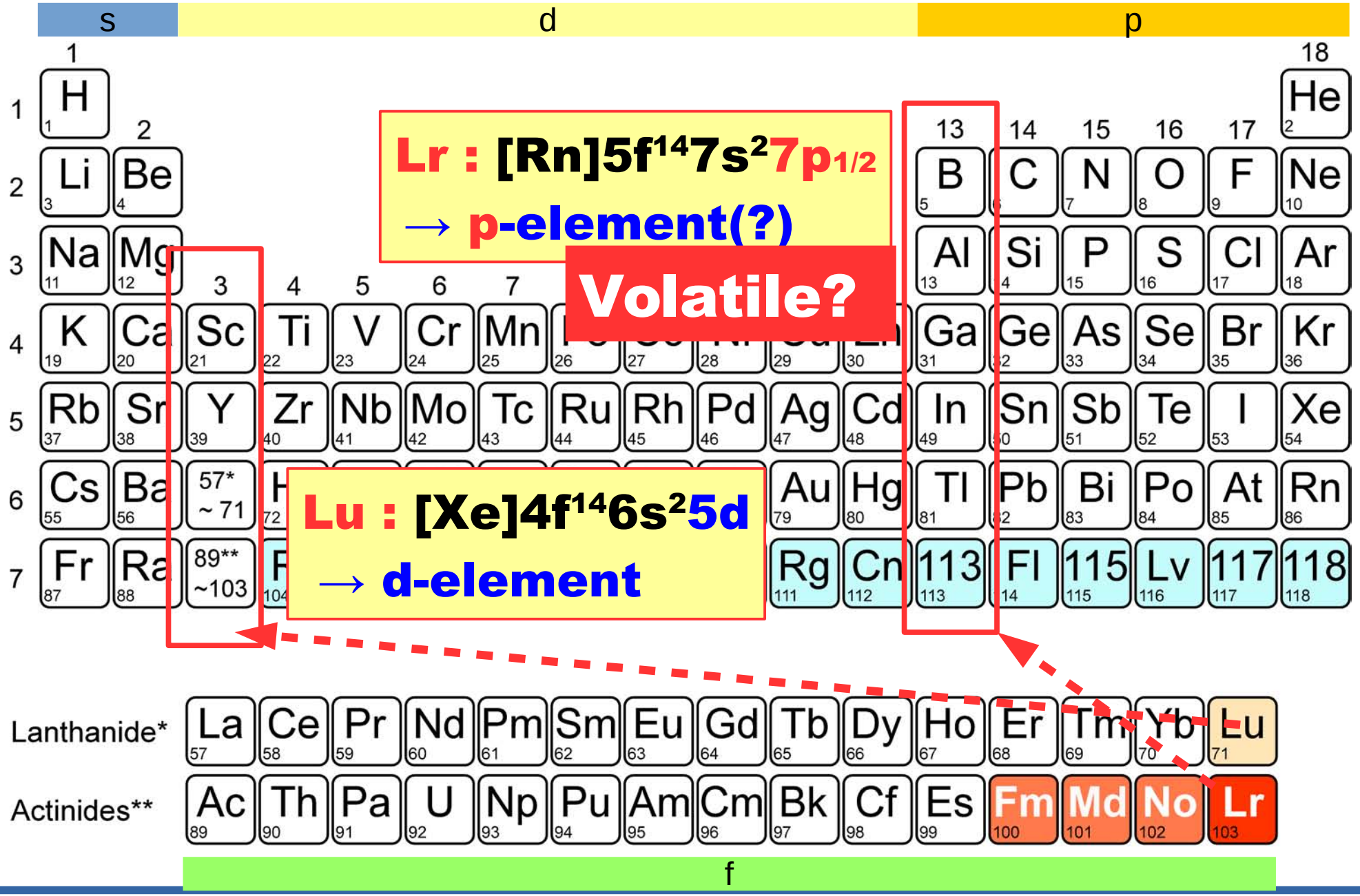
Is Lr a p-element?



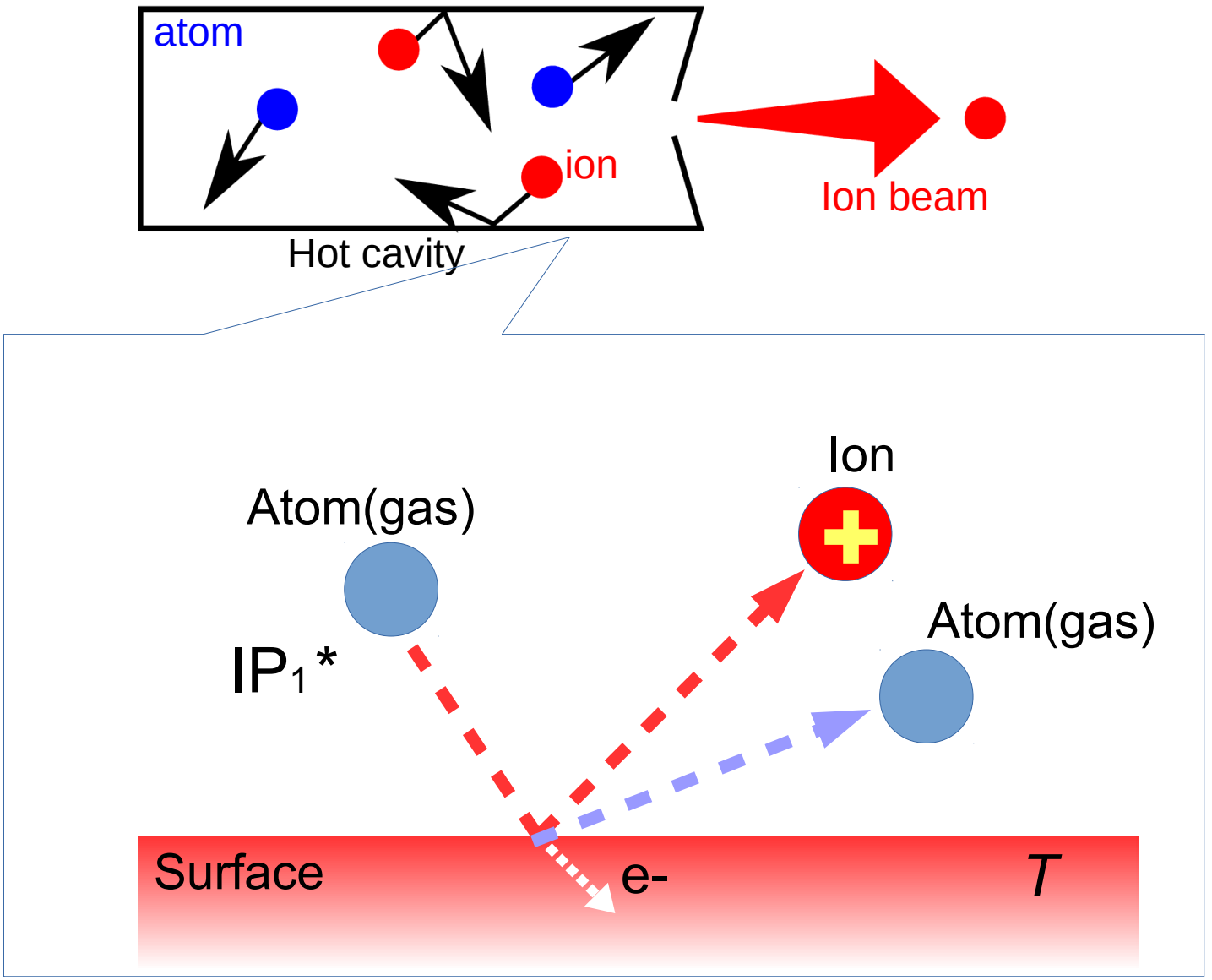
Is Lr a p-element?



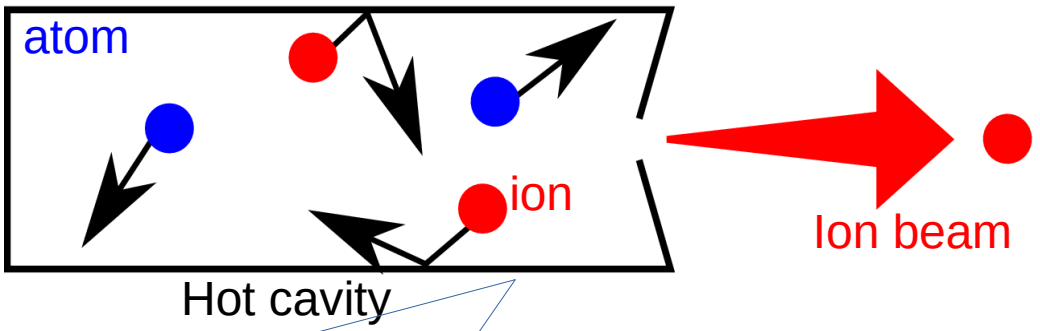
Is Lr a p-element?

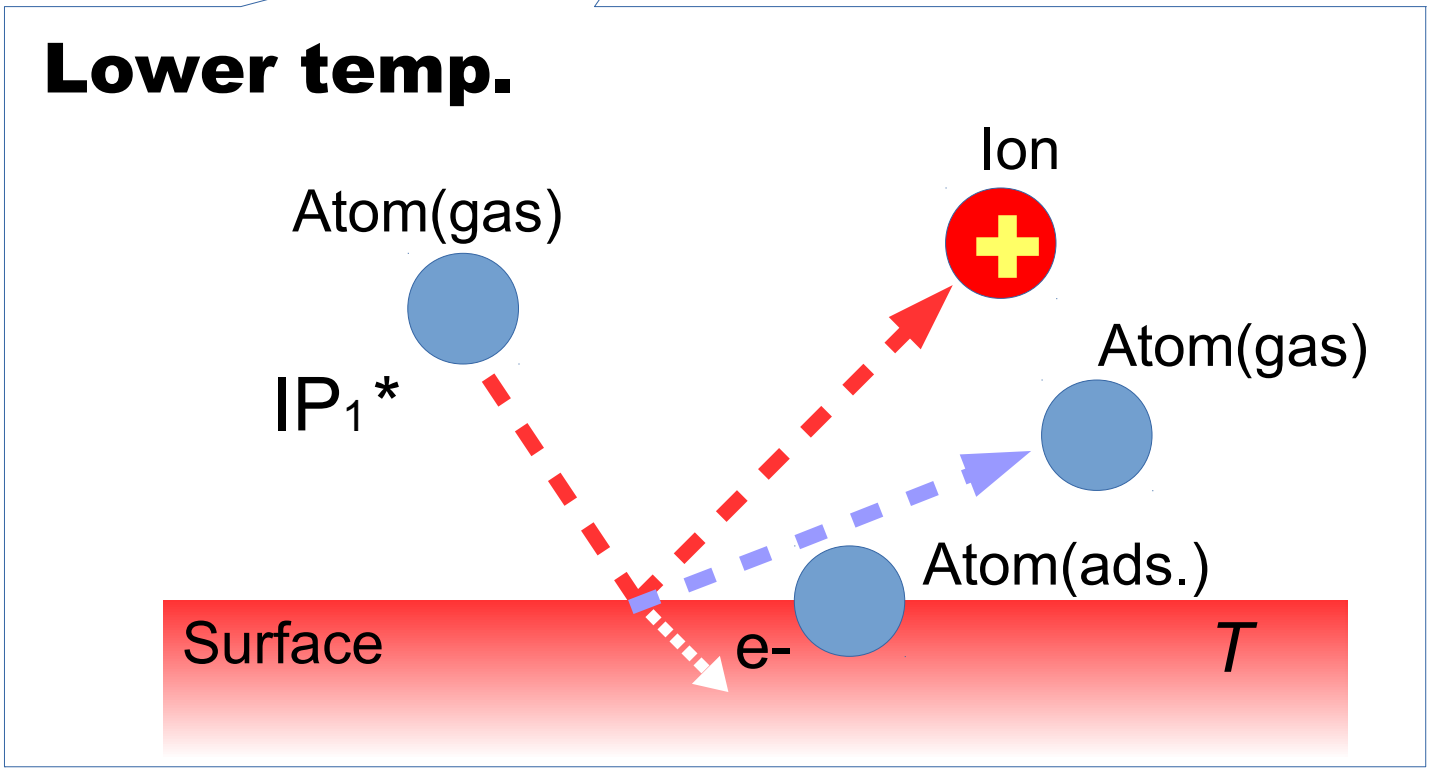


Adsorption on surface of IS

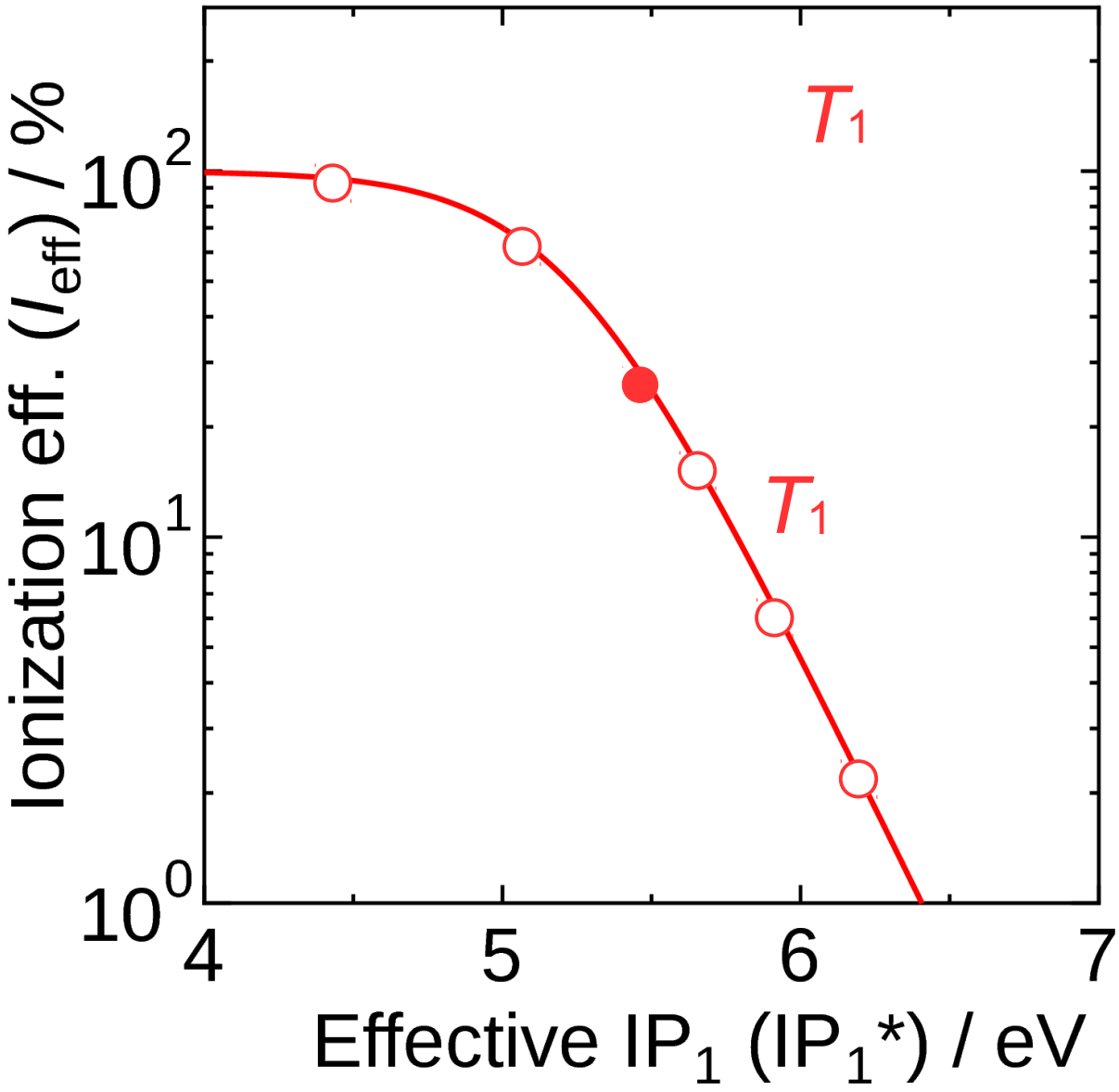


Adsorption on surface of IS





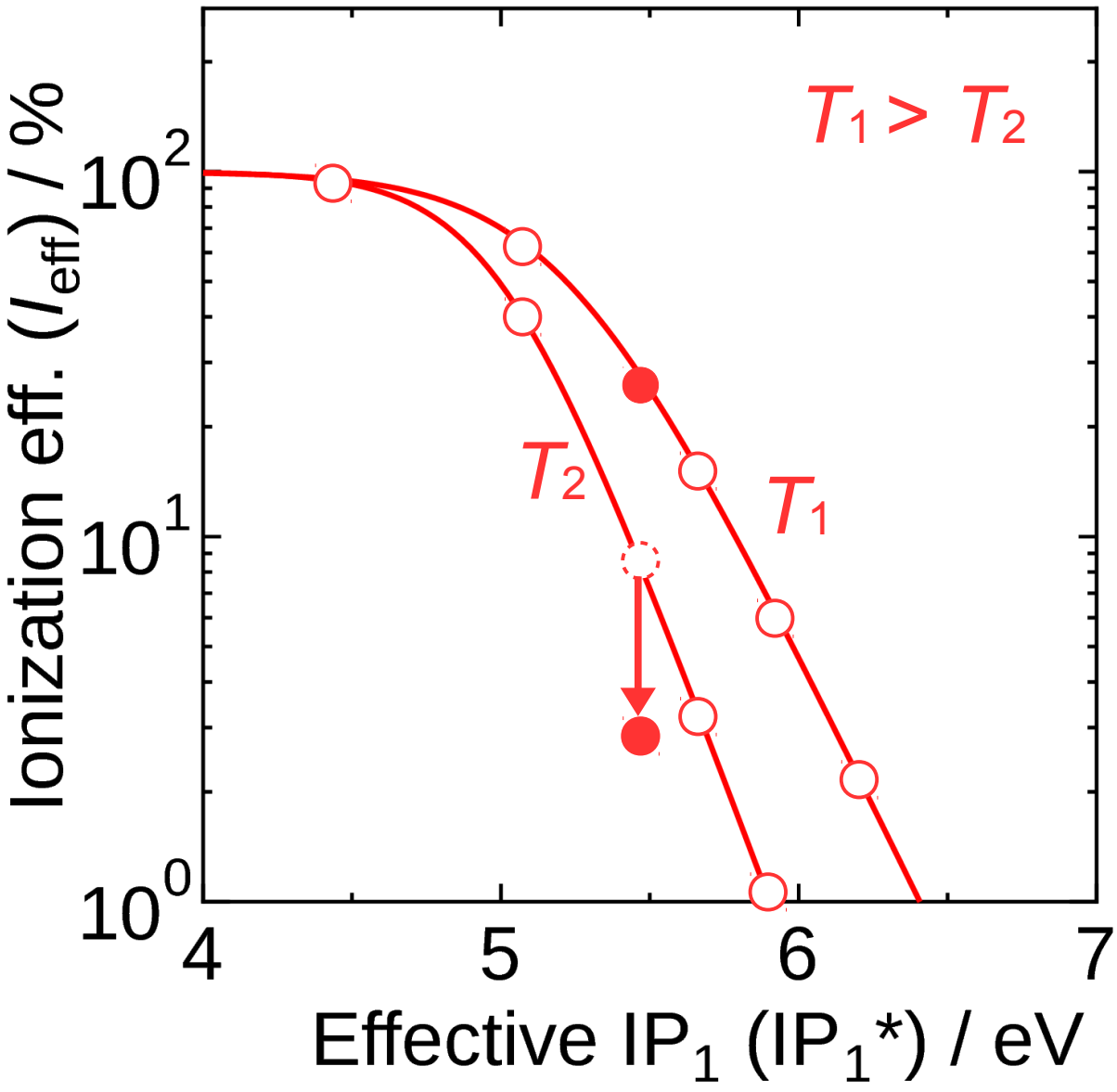
Adsorption on surface of IS



At T_1

I_{eff}(measured) = I_{eff}(fitted)

Adsorption on surface of IS



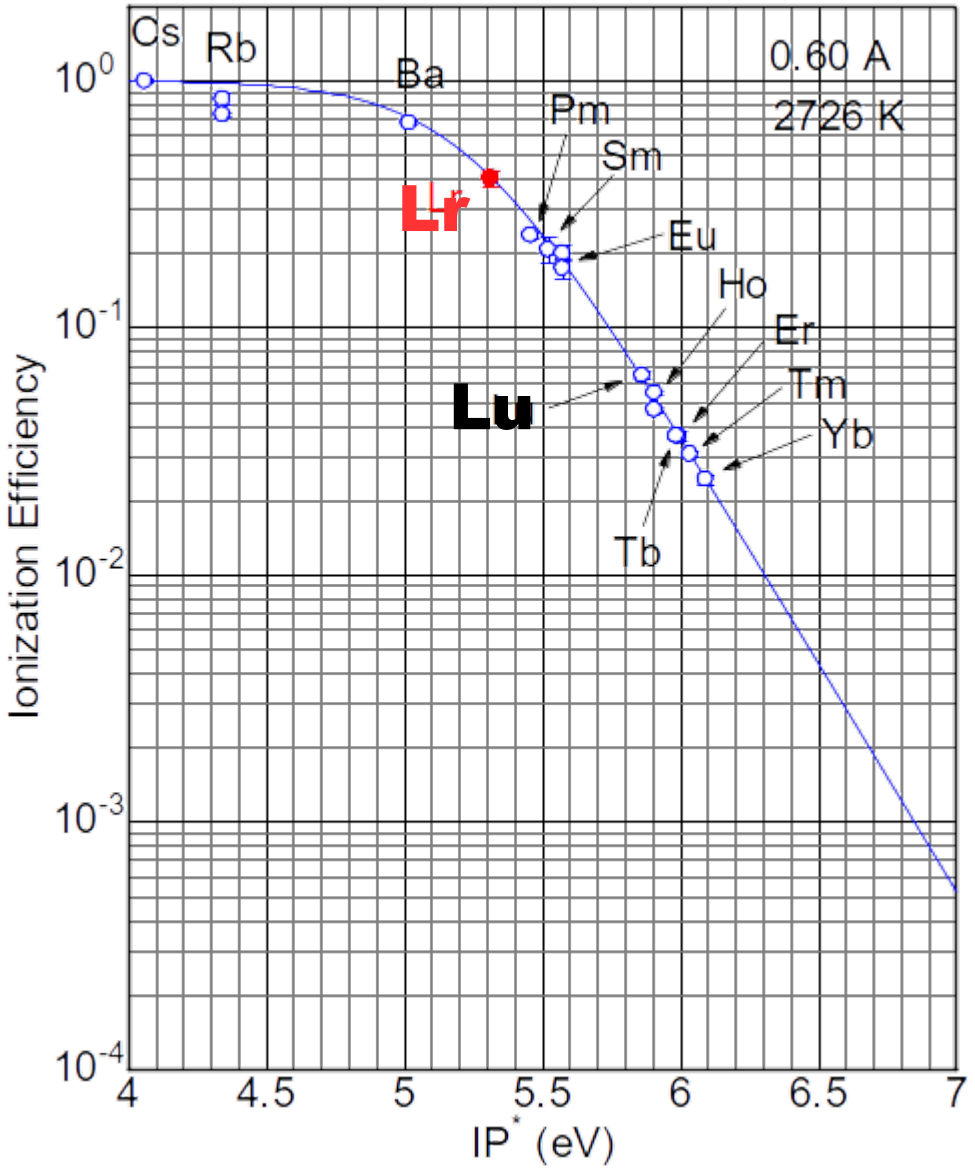
At T_1

I_{eff}(measured) = I_{eff}(fitted)

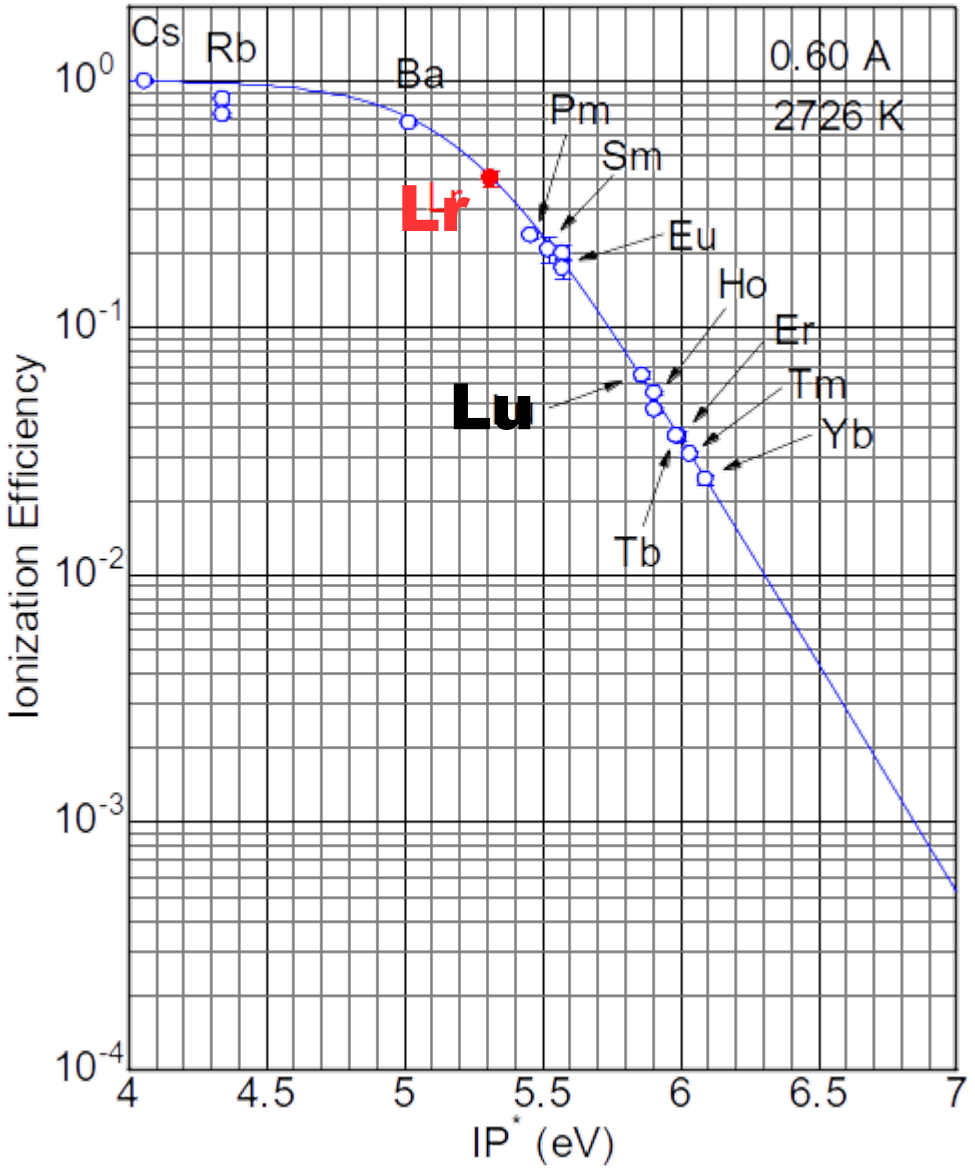
At T_2

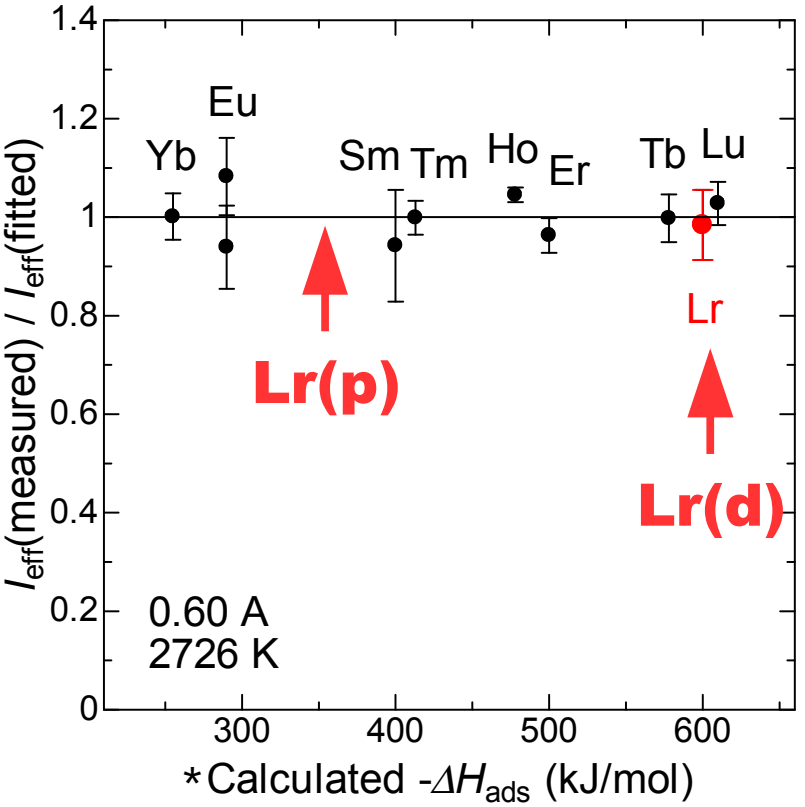
I_{eff}(measured) < I_{eff}(fitted)

Adsorption on surface of IS



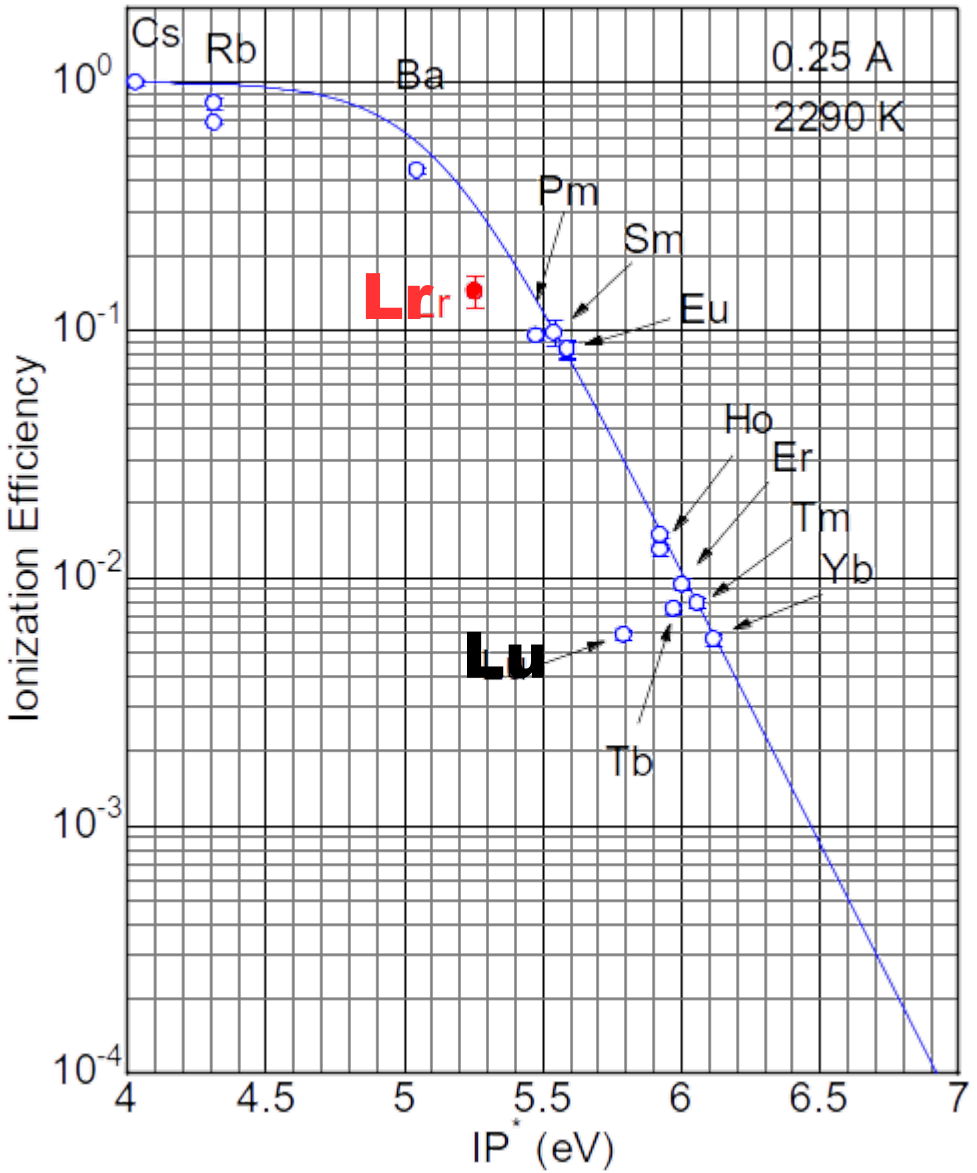
Adsorption on surface of IS

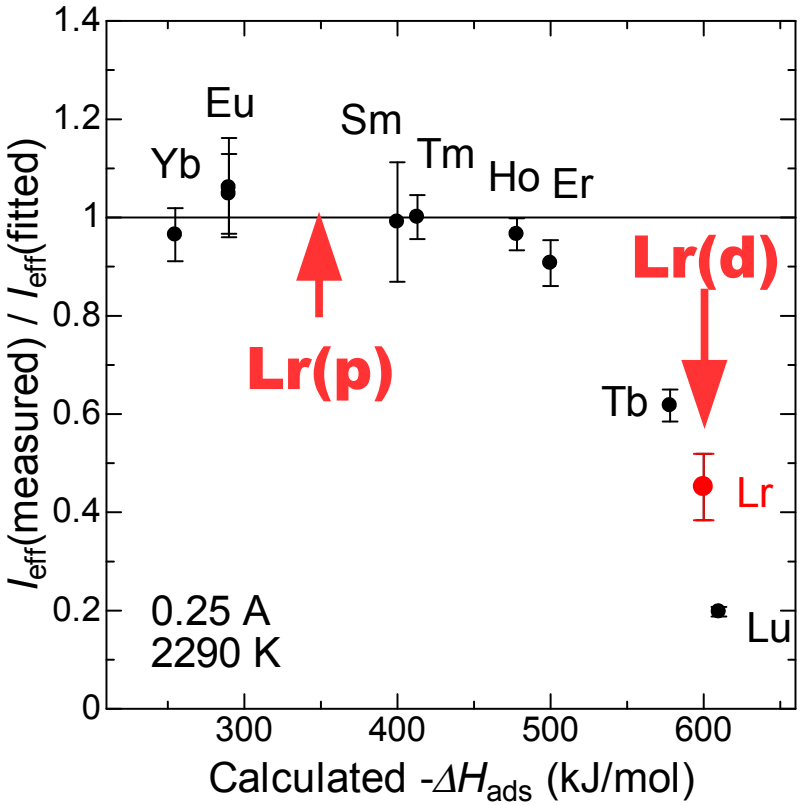




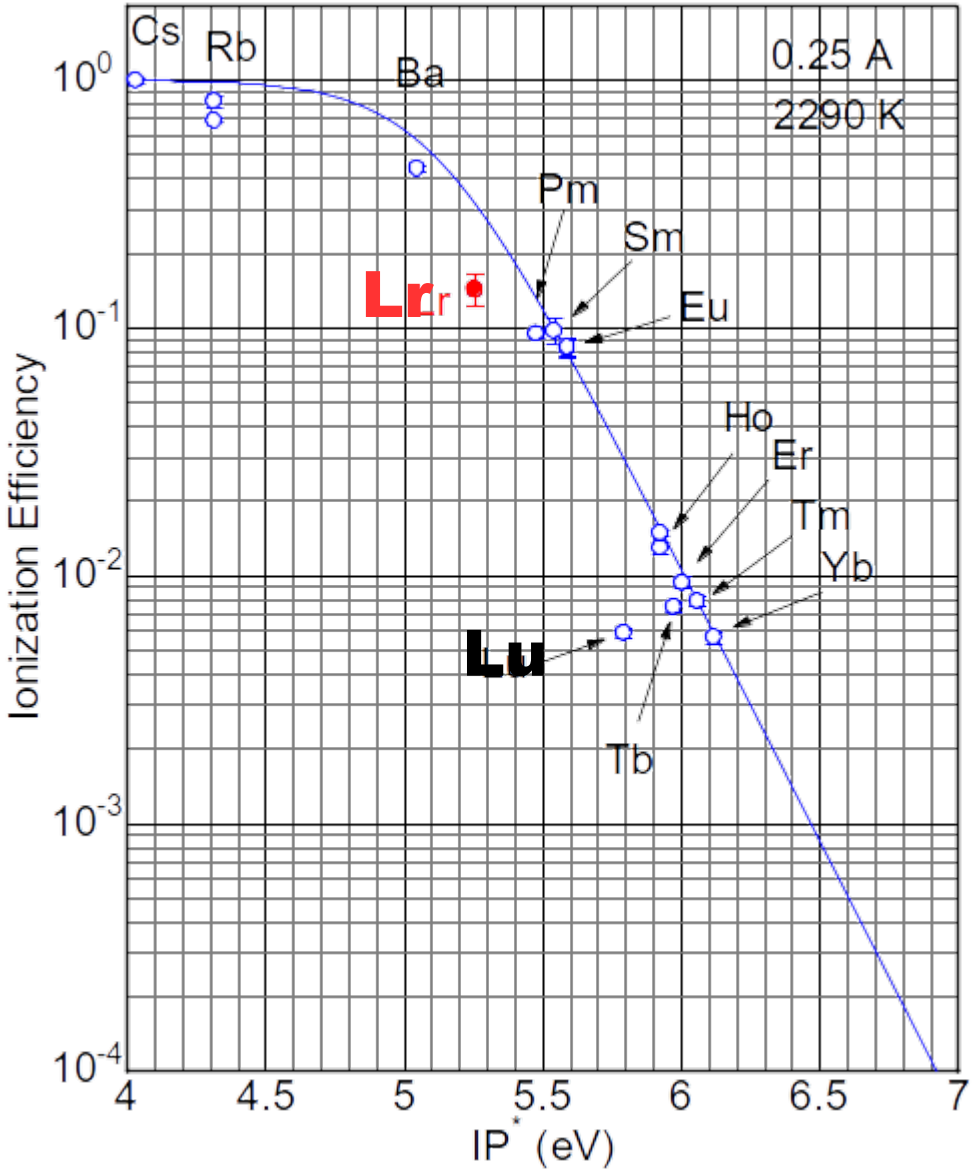
* R. Eichler, private communication

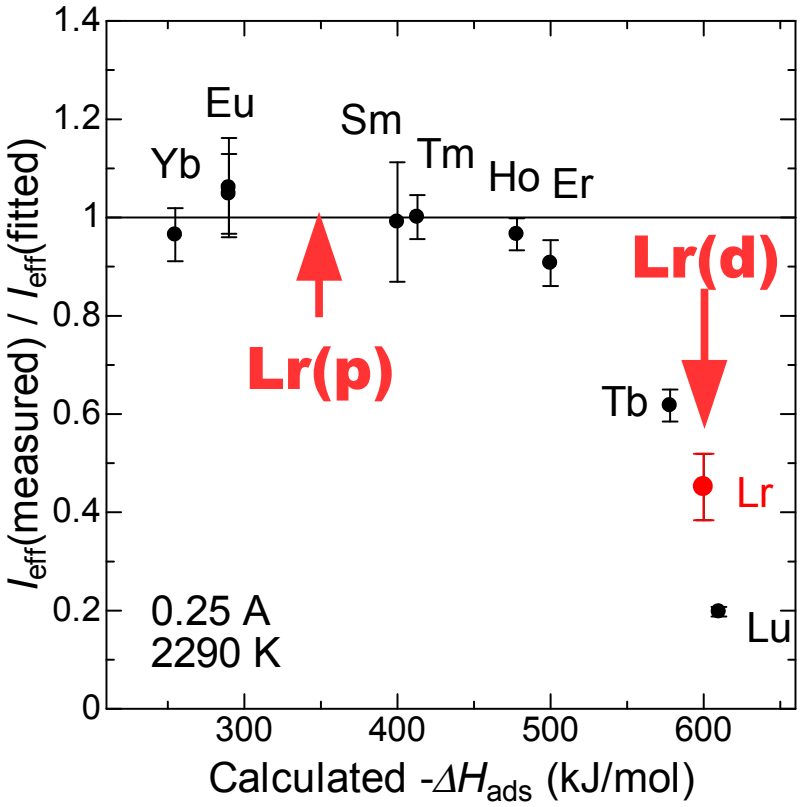
Adsorption on surface of IS





Adsorption on surface of IS





Lr would have a $7p_{1/2}$ electron in the valence orbital like p-element, but its volatility could be similar with that of d-element.