First Ionization Potential Measurements of Heaviest Actinides

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14th Workshop on
Recoil Separator for Superheavy Element Chemistry

REC SEP @ SHE CHEM

14th Workshop on Recoil Separator
for Super Heavy Element Chemistry (TASCA15)
Oct. 23,2015 @GSI

Contents

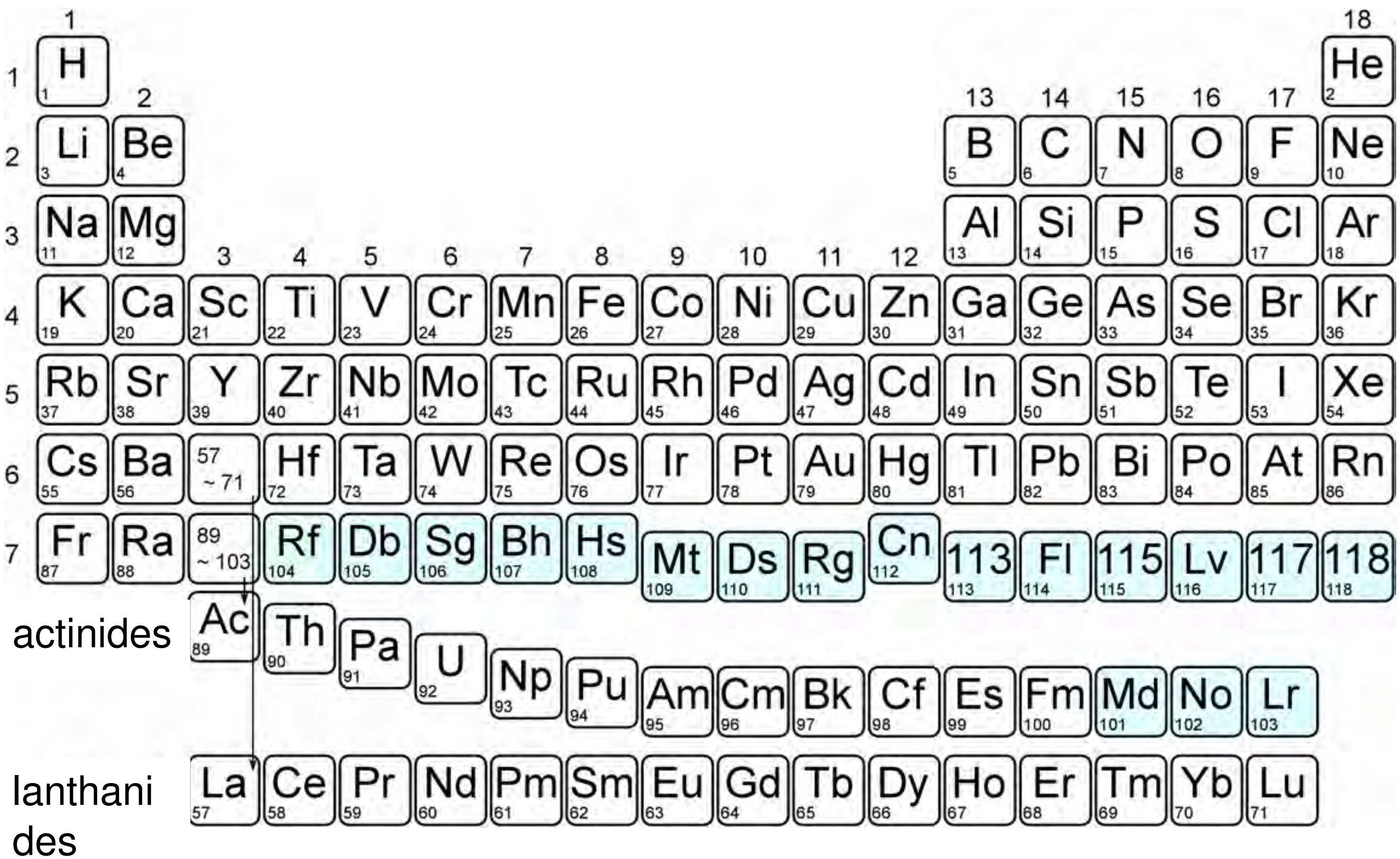
1. Background
   - Ionization potential (IP) of heavy actinides

2. Experimental
   - IP measurement method based on surface ionization process
   - Experimental setup

3. Results
   1. IP of No
   2. IPs of Fm and Md

4. Summary

Super heavy elements



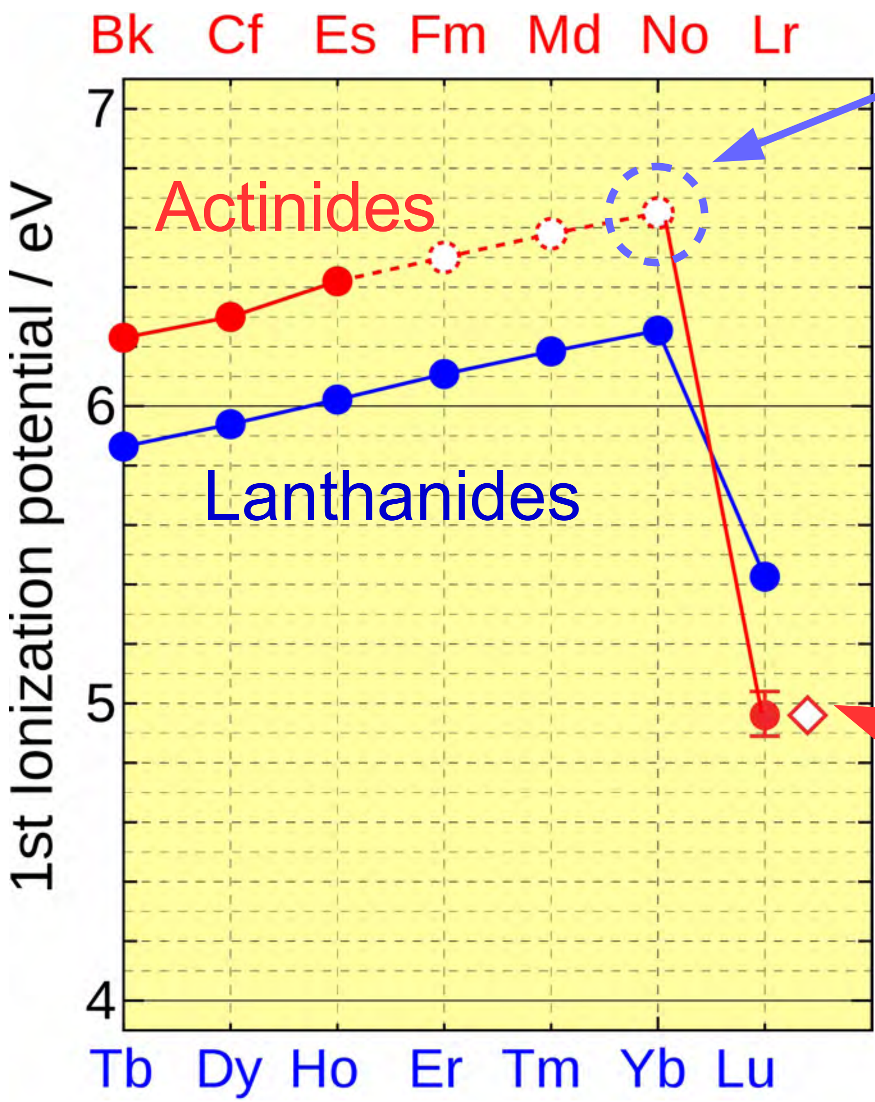
Heavy Elements (Z>100)

Relativistic effects on chem.properties

Short $T_{1/2}$ & Low production rates

IP measurement → direct information of the atom

1st ionization potential (IP_1) of actinides



Estimated by an extrapolation from lighter actinides

No: Full-filled 5f+7s orbitals

→ **Highest IP_1**

End point of the extrapolation

- property of f-block elements

Full-filled 5f+7s orbitals

+ additional $7p_{1/2}$

→ **Lowest IP determined by the surface-ionization method [1].**

[1] T. K. Sato, et al., Nature **520** (2015) 209-211.

Purpose

Information on the electronic configuration of heavy actinides

➡ Experimental determination of IP

⬆

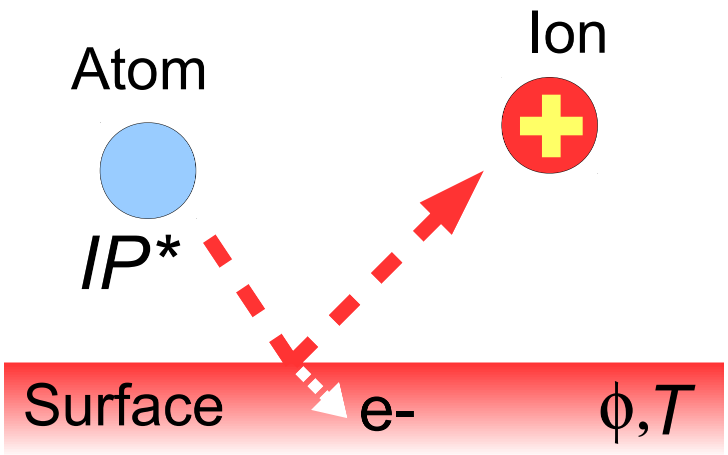
Surface ionization method

Surface ionization

Saha-Langmuir eq.

$$\begin{cases} \alpha = \dfrac{N^+}{N^0} = \exp\left(\dfrac{\varphi - IP^*}{kT}\right) \\ \text{Effective IP}_1(\text{IP}_1^*) : IP_1^* = IP_1 - kT \ln(Q_i/Q_o) \end{cases}$$

N^+ and N^o: numbers of ions and atoms
φ : work function [eV]
T: surface temperature [K]
Q_i and Q_o: partition functions of ion and atom
IP_1 : 1st ionization potential



Surface ionization

Saha-Langmuir eq.

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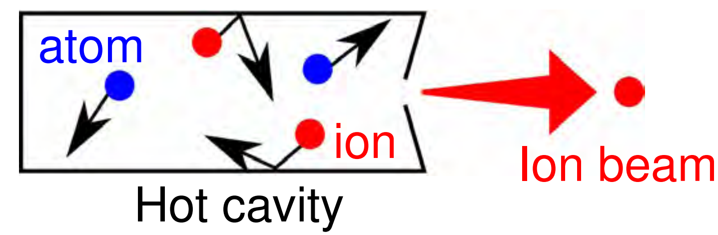
Q_i and Q_o: partition functions of ion and atom
IP_1 : 1st ionization potential

Cavity effect in surface IS

$$\text{Ionization eff.} = \frac{N\alpha}{1 + N\alpha}$$

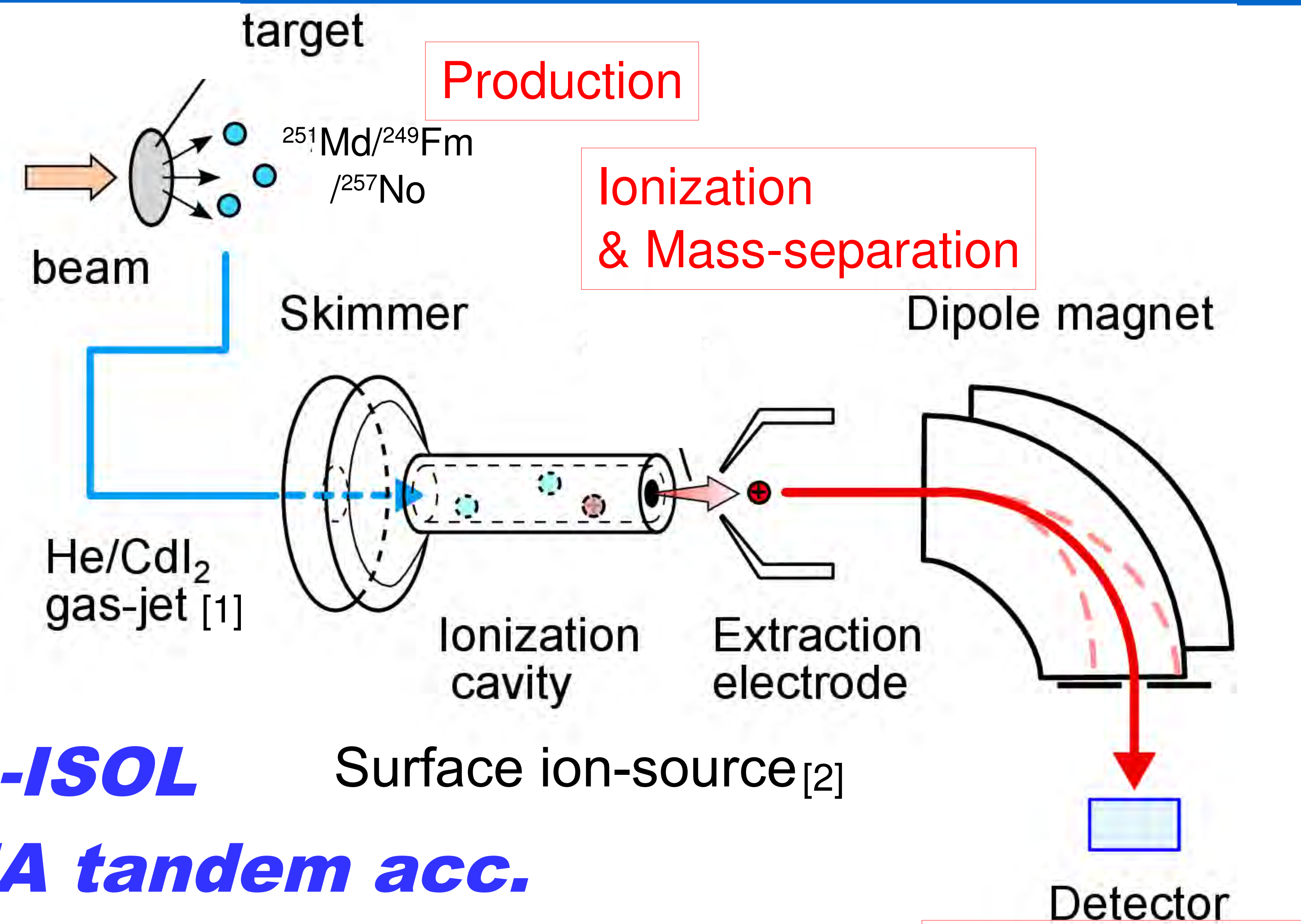
N : number of collisions of an atom with a surface



$$I_{eff} = \frac{N \exp\left(\left(\varphi - IP_1^*\right)/kT\right)}{1 + N \exp\left(\left(\varphi - IP_1^*\right)/kT\right)}$$

Ionization eff. (I_{eff}) → Effective IP₁ (IP_1^*) → IP_1

Experimental setup

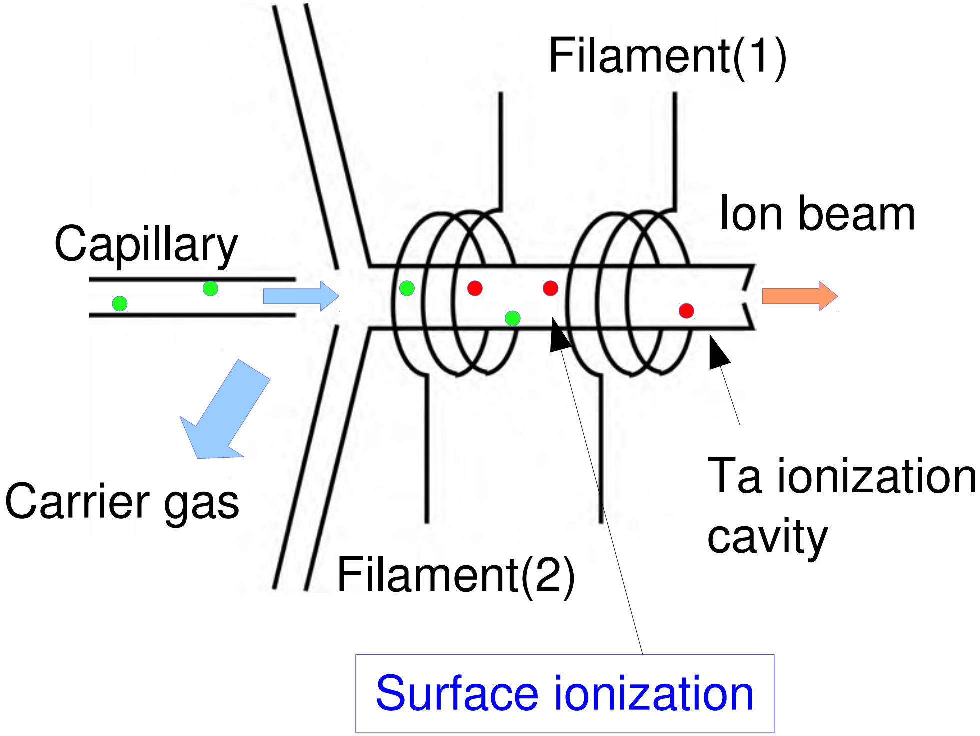


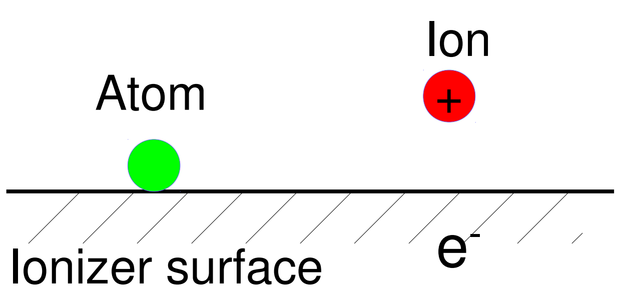
JAEA-ISOL

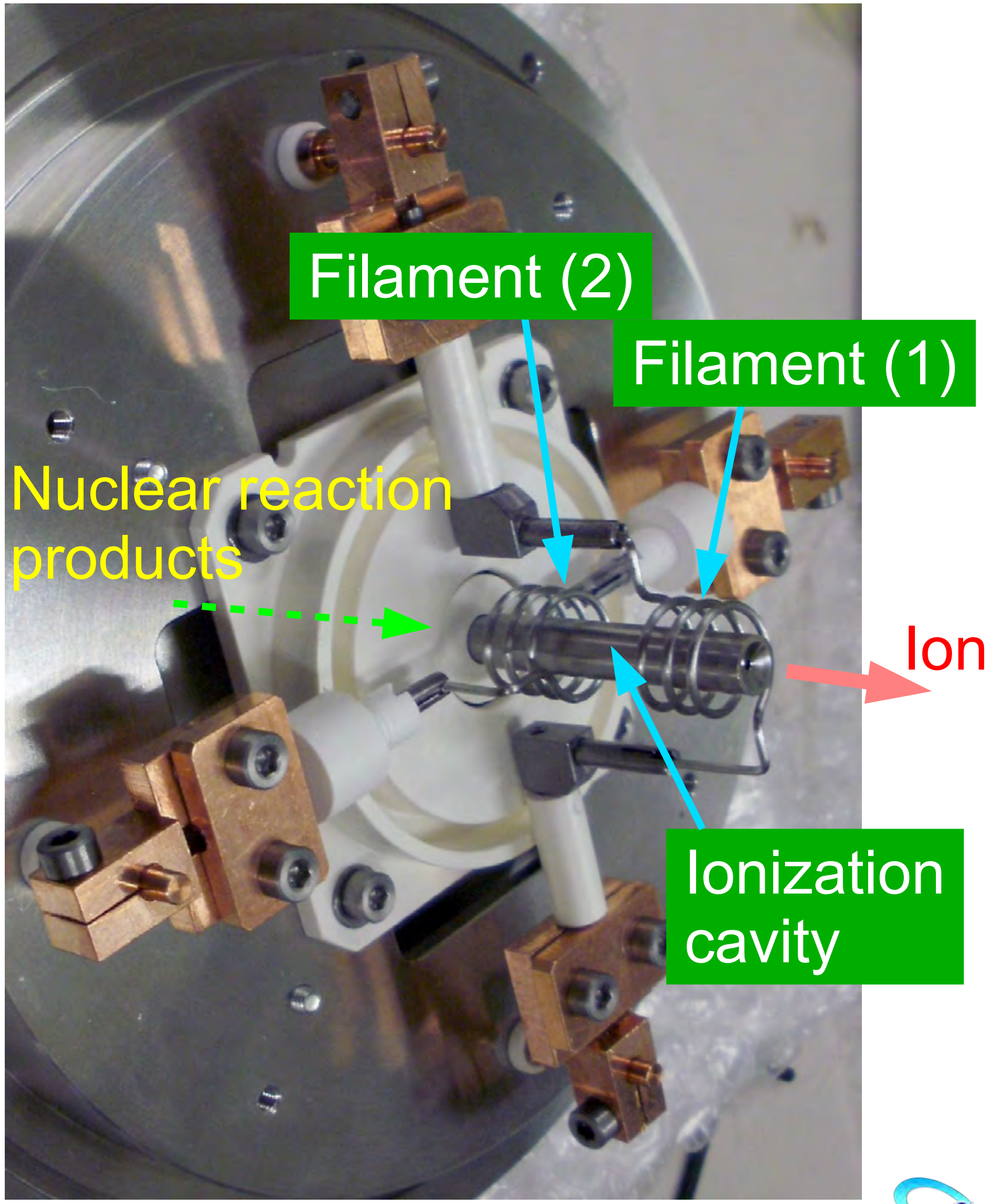
@JAEA tandem acc.

[1] T.K.Sato et al JRNC, 303, 1253-1257 (2015).
[2] T.K.Sato et al RSI, 84, 023304 (2013).

Surface ion-source







IP measurement of No

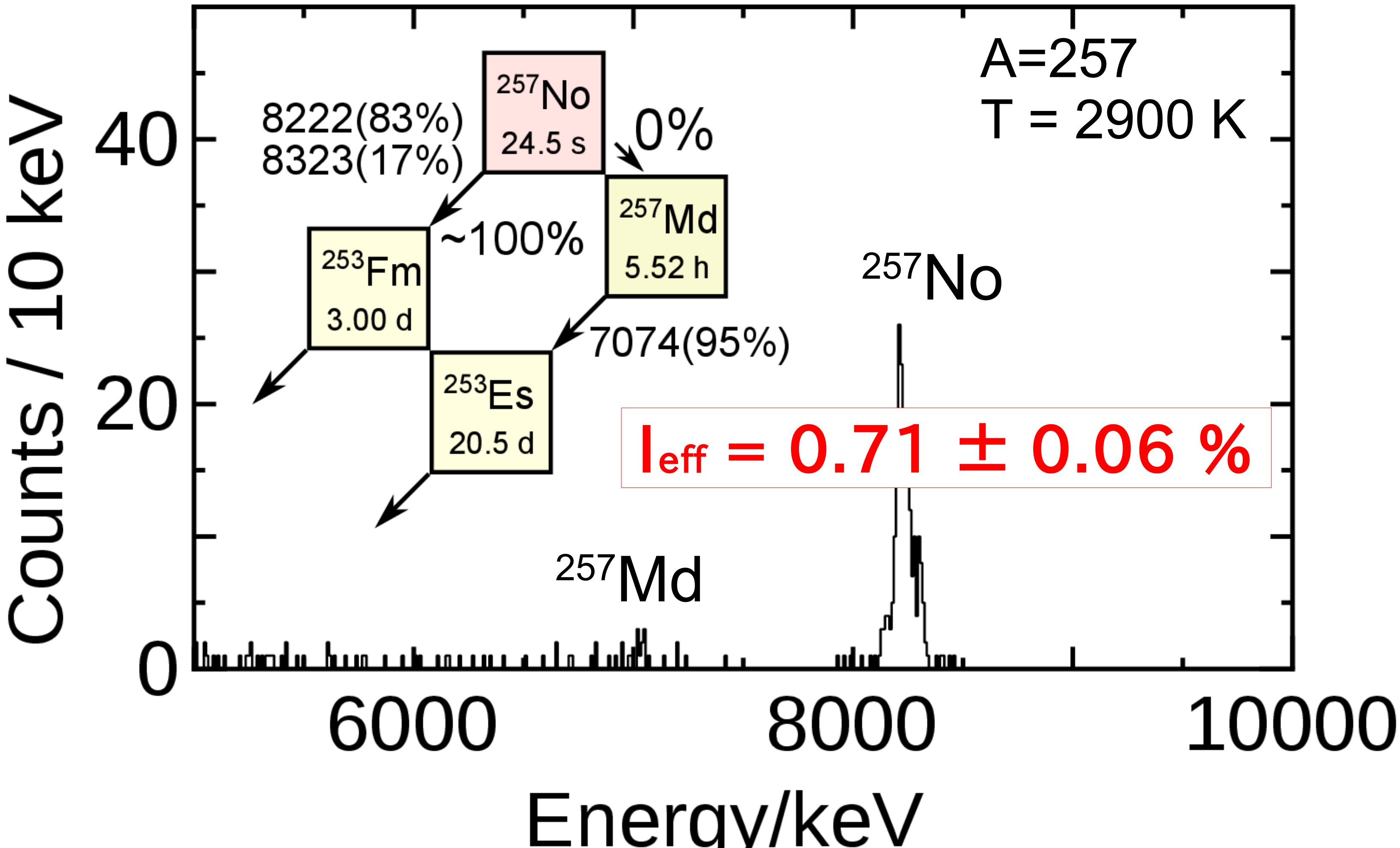
Ionization of ^{257}No

Isotope : ^{257}No ($T_{1/2}$ = 24.5 s)

Beam : ^{13}C (76 MeV)

Target : ^{248}Cm (eff.390 μg/cm^2)

Ionization temp.: 2900K



Ionization eff.(I_{eff}) of Ln isotopes

Isotopes : ^{80}Rb, $^{142,143}Eu$, ^{143}Sm, ^{148}Tb, $^{153,154}Ho$, ^{157}Er, ^{162}Tm, ^{165}Yb, ^{168}Lu, ^{49}Cr

Beam : ^{11}B(67.9 MeV)

Targets : ^{136}Ce, ^{141}Pr, ^{142}Nd, ^{147}Sm, Eu, ^{156}Gd, ^{159}Tb, ^{162}Dy, ^{45}Sc and Ge

$$I_{eff} = \frac{N \exp\left(\left(\varphi - IP_1^*\right)/kT\right)}{1 + N \exp\left(\left(\varphi - IP_1^*\right)/kT\right)}$$

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

S-L eq.

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

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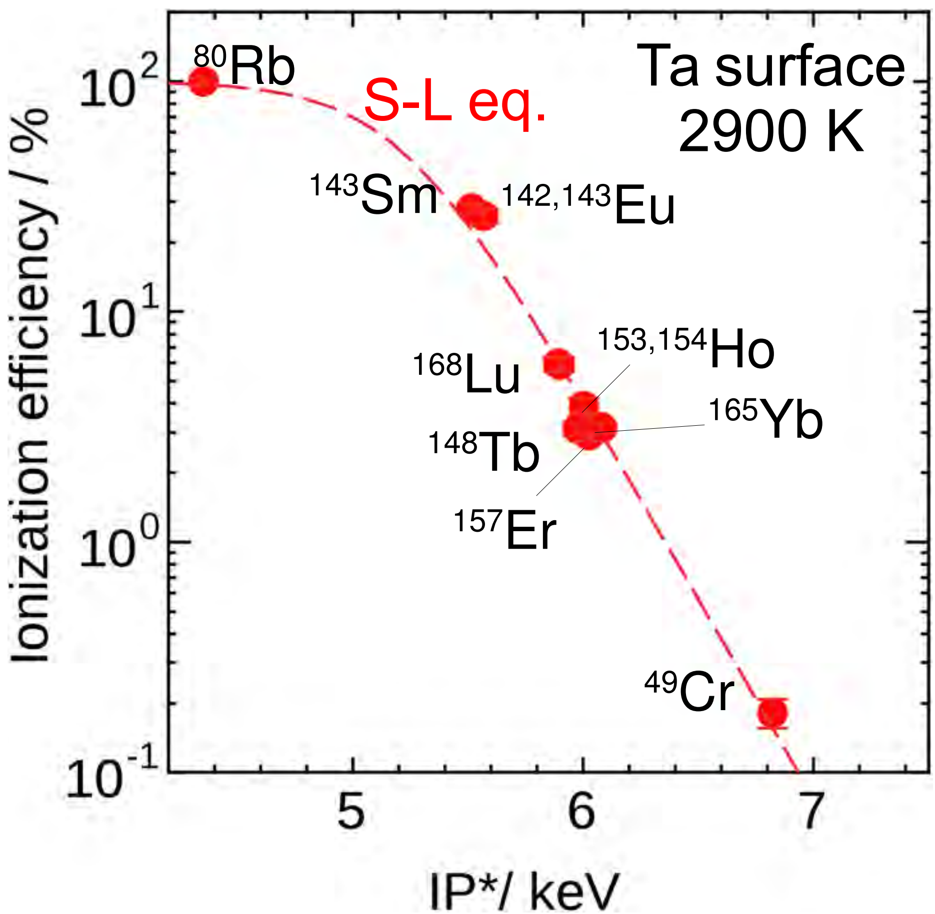
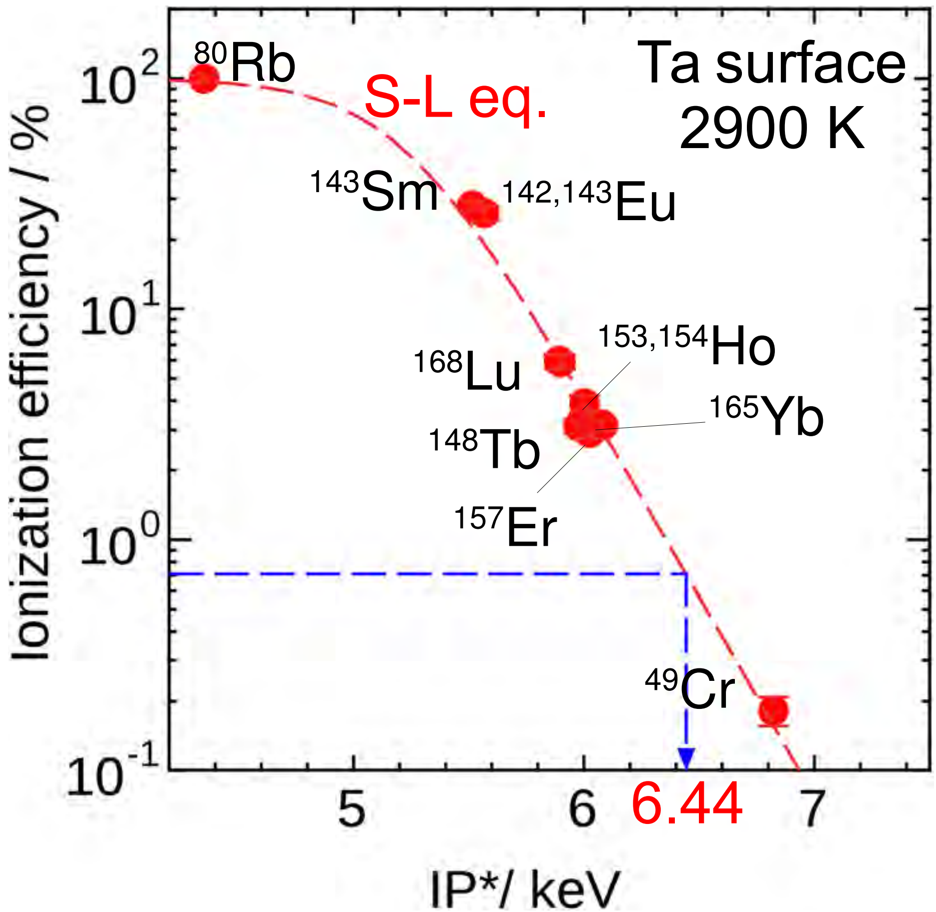


S-L eq.

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

I_{eff} (No) on IP^*-I_{eff} curve



I_{eff}(No) = 0.71±0.06%

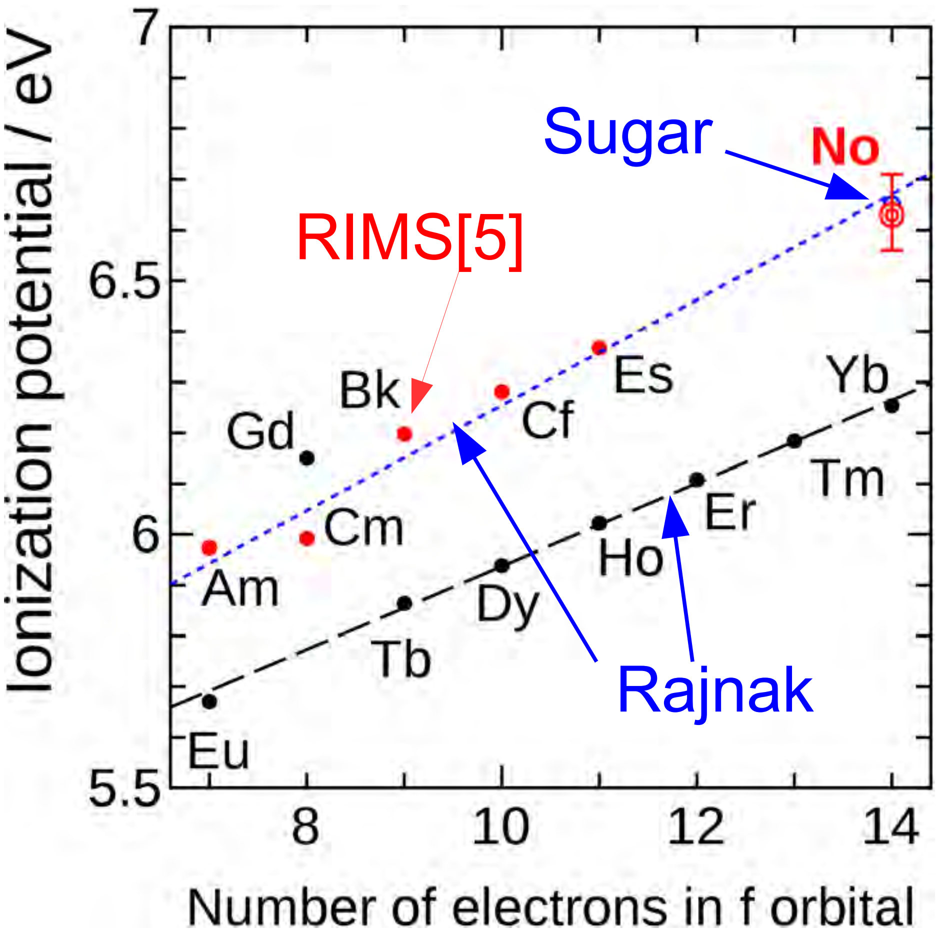
IP_1^*(No)=6.44 eV

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

IP_1(No) = 6.63±0.08 eV

(Preliminary)

1st ionization potential (IP_1) of No



Semi-empirical

J. Sugar [1] 6.65 ± 0.07 eV

K. Rajnak [2] IP=0.1039N+5.216
= 6.67 eV

Theoretical calc.

A. Borschevsky [3] 6.632 eV

V.A. Dzuba [4] 6.743 eV

Experimental (This work)

IP_1(No) = 6.63±0.08 eV
(Preliminary)

[1] J. Sugar, J. Chem. Phys. 60 (1974) 4103.
[2] K. Rajnak et al. J. Opt. Soc. Am. 68 (1978) 360.
[3] A. Borschevsky et al. Phys. Rev. A75, 042514 (2007).
[4] V.A.Dzuba et al. Phys. Rev. A90, 012504 (2014).
[5] N. Erdmann et al. J. Alloy. Comp. 271-273 (1998) 837.

IP measurements of Md/Fm

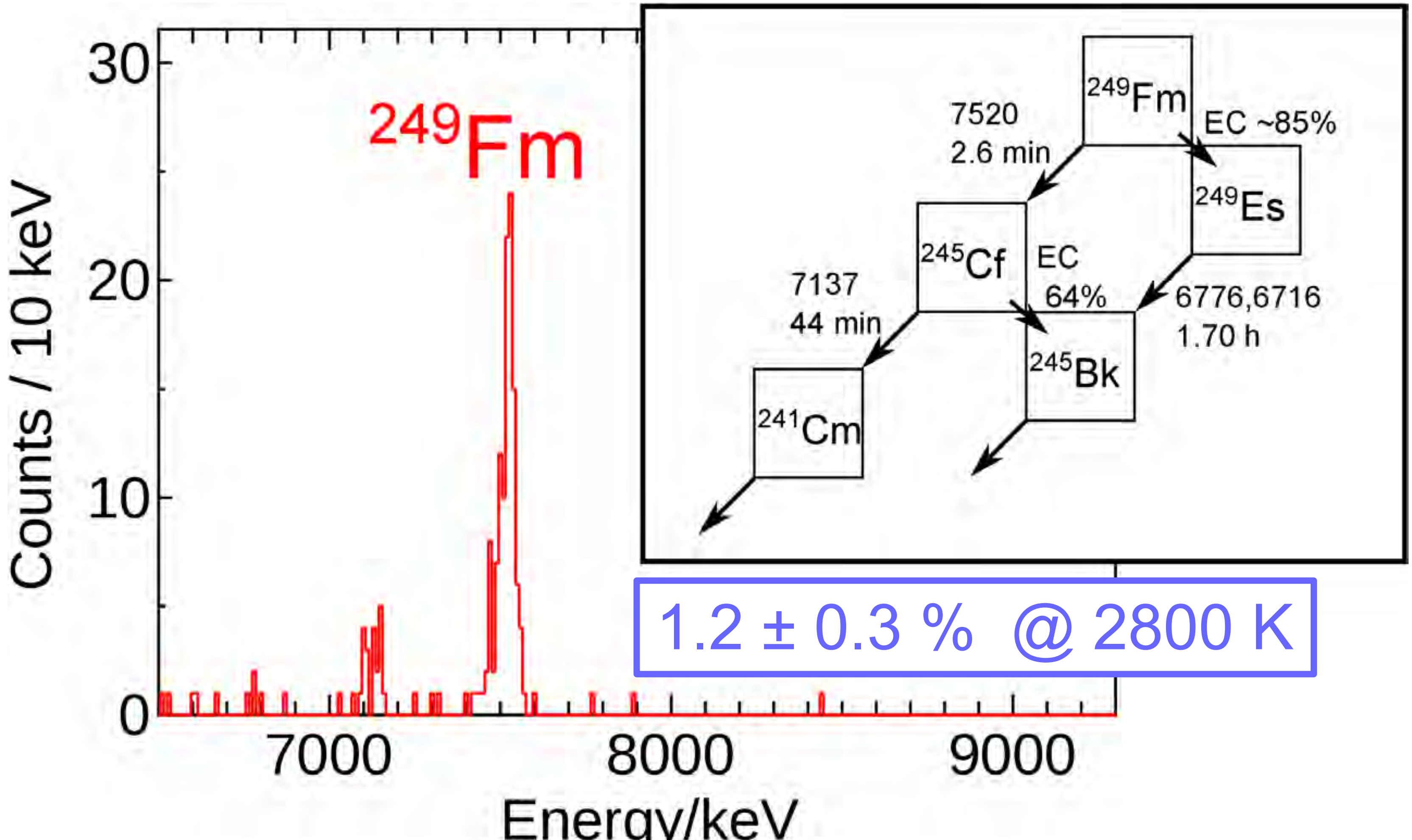
Ionization of ^{249}Fm

Fermium

$_{100}$Fm

^{249}Fm ($T_{1/2}$ = 2.6 min.)

Reaction : ^{243}Am(^{11}B, 5n)

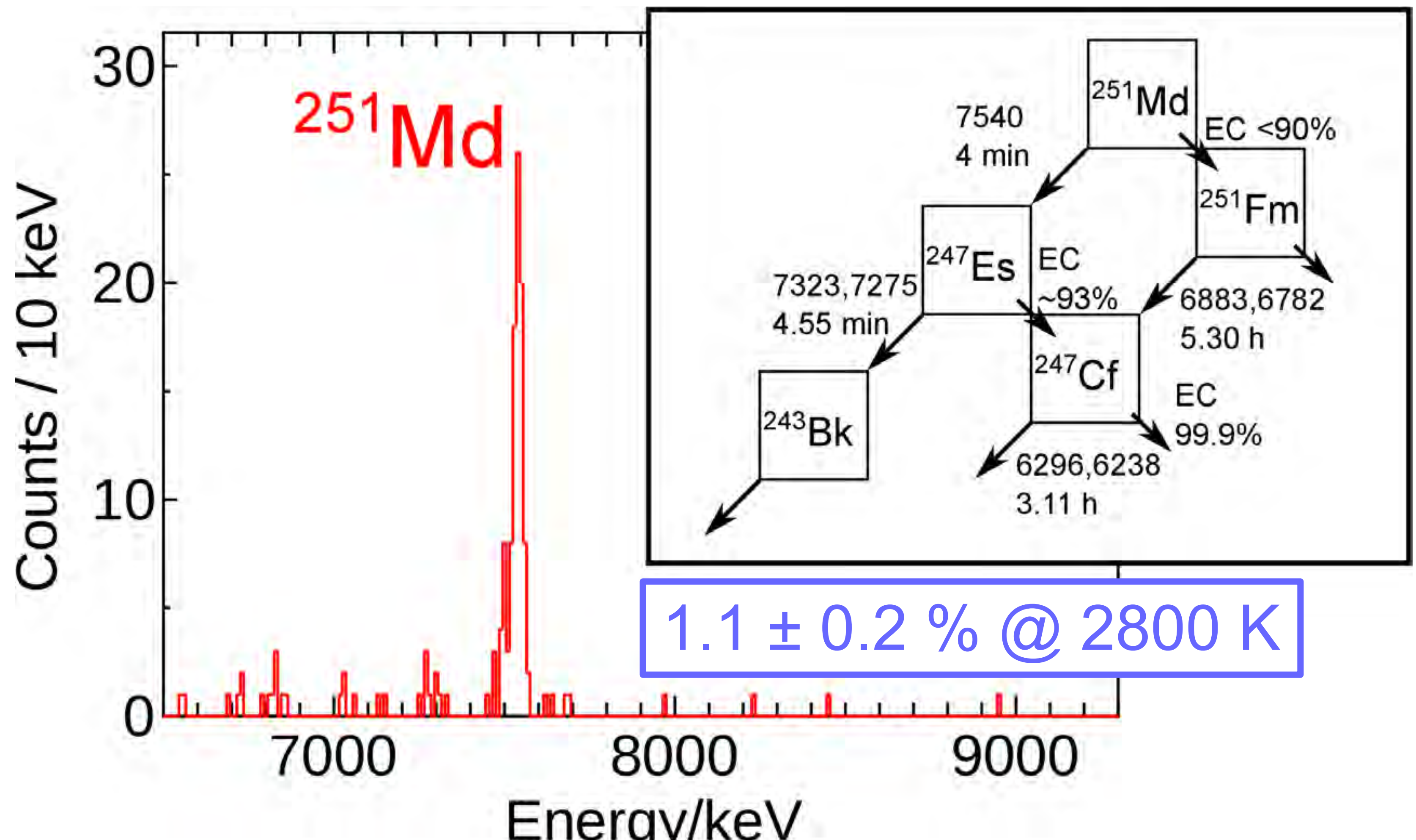


1.2 ± 0.3 % @ 2800 K

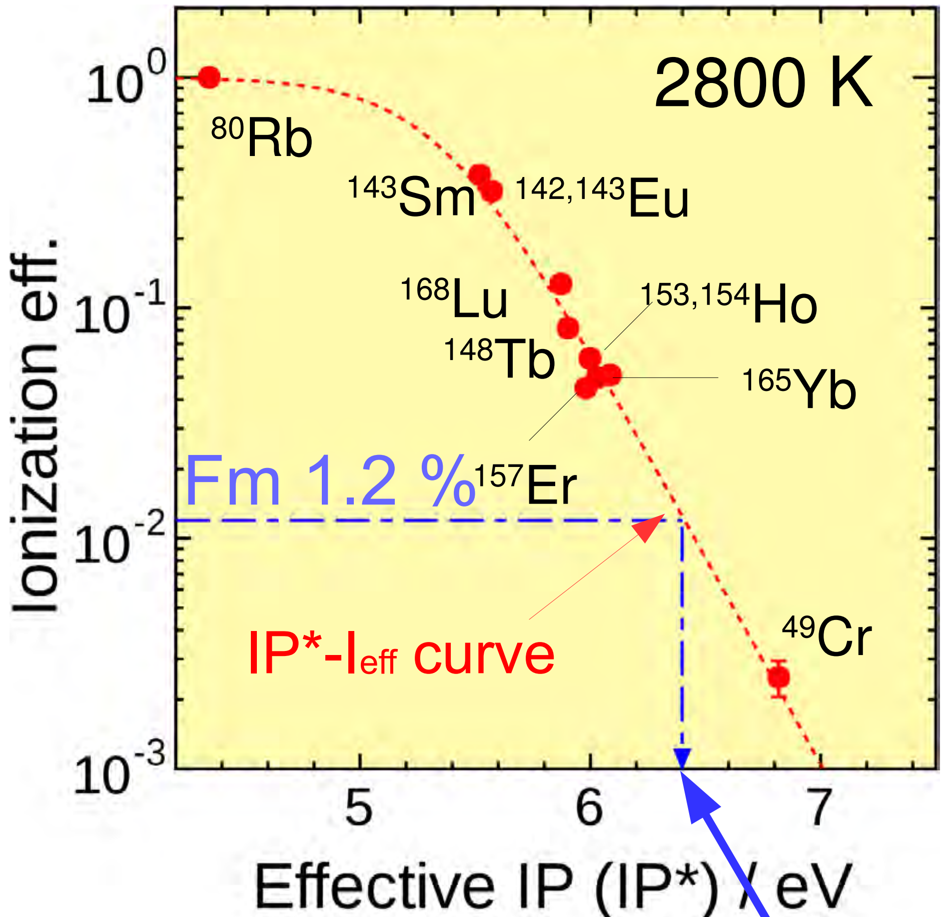
Ionization of ^{251}Md

Mendelevium
$_{101}$Md

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



I_{eff} (Fm, Md) on IP*-I_{eff} curve

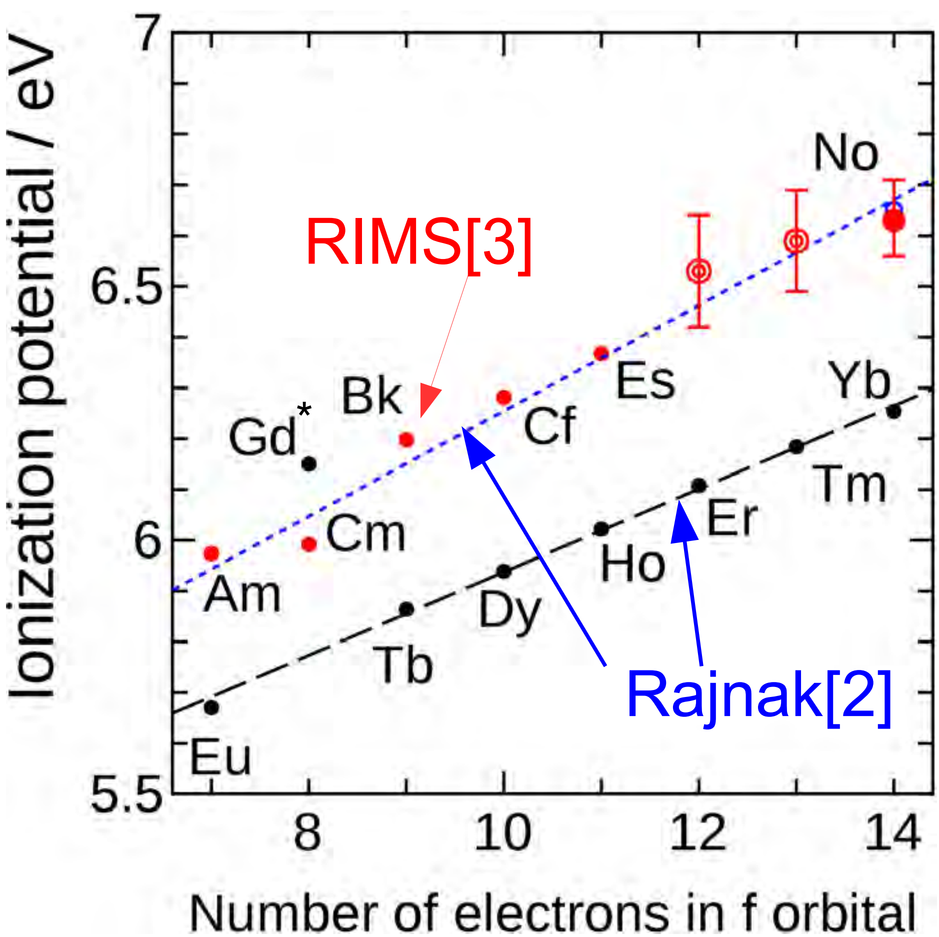


IP*(Fm) = 6.41 eV

I_{eff}	Fm: 1.2 ± 0.3 % Md: 1.1 ± 0.2 %
IP*	Fm: 6.41 ± 0.11 eV Md: 6.44 ± 0.10 eV
IP	Fm: 6.53 ± 0.11 eV Md: 6.59 ± 0.10 eV

Preliminary

Summary



Fm		
6.50 ± 0.07		J.Sugar[1]
0.1039N+5.216= 6.46		K.Rajnak
< 6.7		M.Sewtz[4]
6.53 ± 0.11		This work
Md		
6.58 ± 0.07		J.Sugar
0.1039N+5.216= 6.58		K.Rajnak
6.59 ± 0.10		This work

[1] J. Sugar, J. Chem. Phys. 60 (1974) 4103.
[2] K. Rajnak, *et al.* J. Opt. Soc. Am. 68 (1978) 360.
[3] N. Erdmann, *et al*. J. Alloy. Comp. 271-273 (1998) 837.
[4] M. Sewtz, *et al*. PRL 90 (2003) 163002-1.

Summary

- We successfully determined IP values of the heaviest actinide elements, No (Z=102), Md (Z=101) and Fm (Z=100).

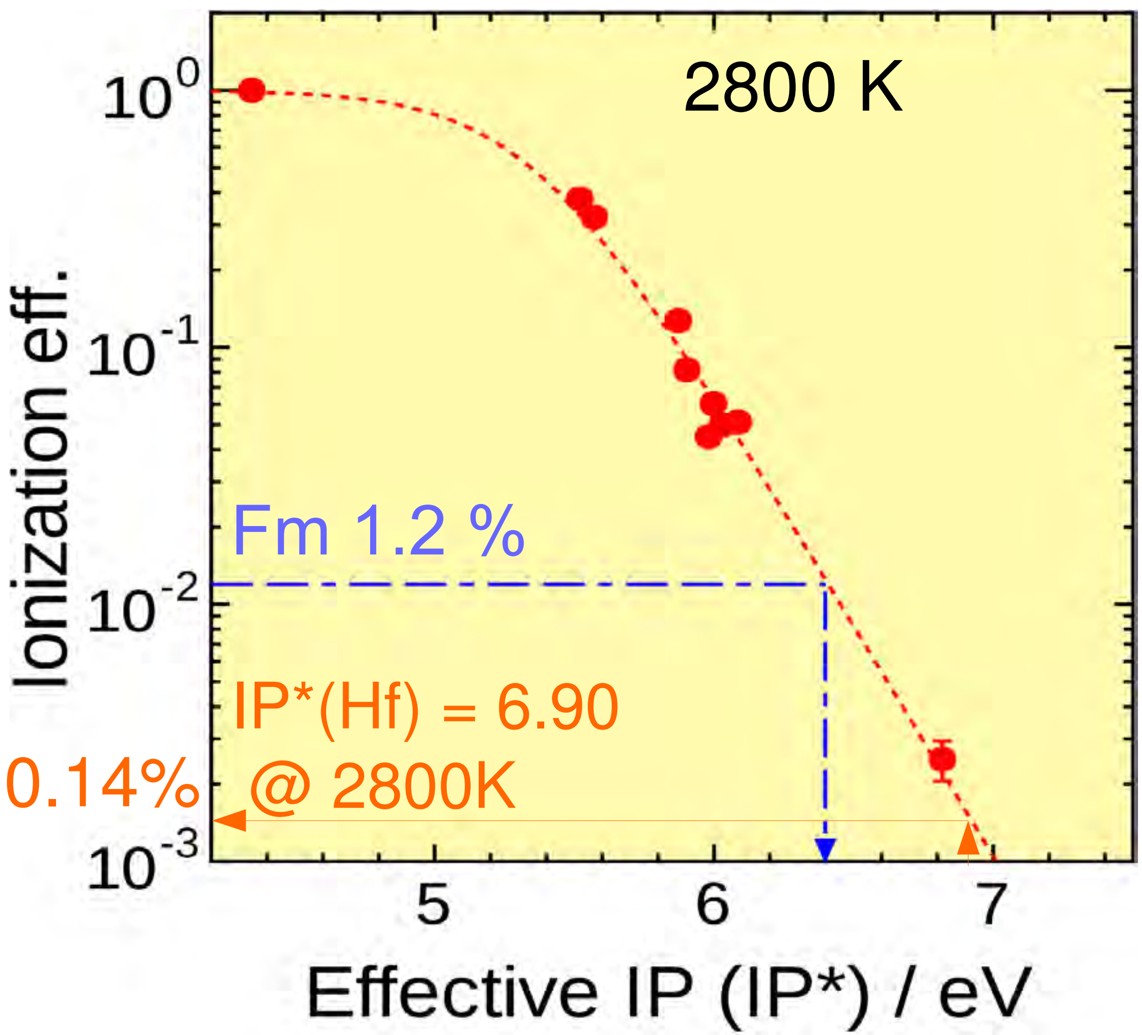
No: 6.63 ± 0.08 eV
Fm: 6.53 ± 0.11 eV
Md: 6.59 ± 0.10 eV

Preliminary

- Obtained IP values are in good agreement with estimated values.
- IP values would increase monotonically with Z.

Is it possible to determine IP value of Rf by the surface-ionization method?

Hf ionization



^{167}Hf ($T_{1/2}$ = 2.05 min.)

Reaction : ^{158}Dy(^{12}C, 3n)