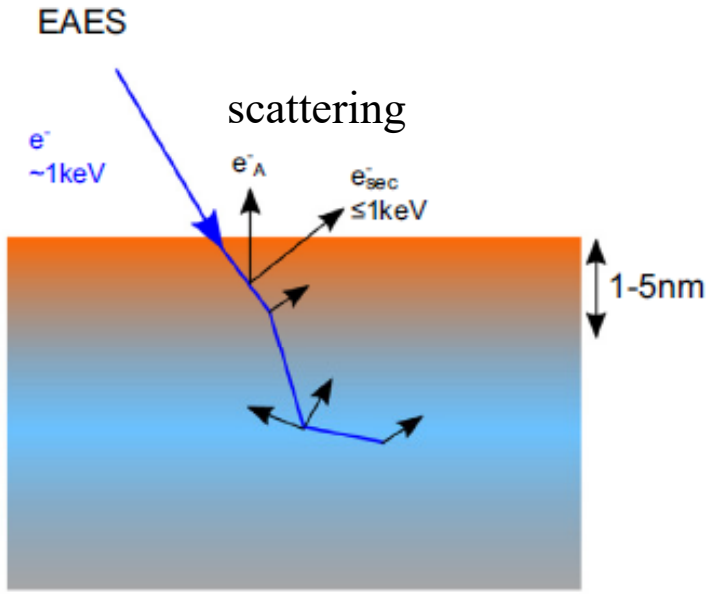
Positron induced Auger-electron spectroscopy (PAES)

- **conventional Auger-electron spectroscopy (AES):**
  - ***electron induced Auger-electron spectroscopy (EAES)***
  - ***photon induced Auger-electron spectroscopy (XAES)***

several nm sub-surface region ⟷

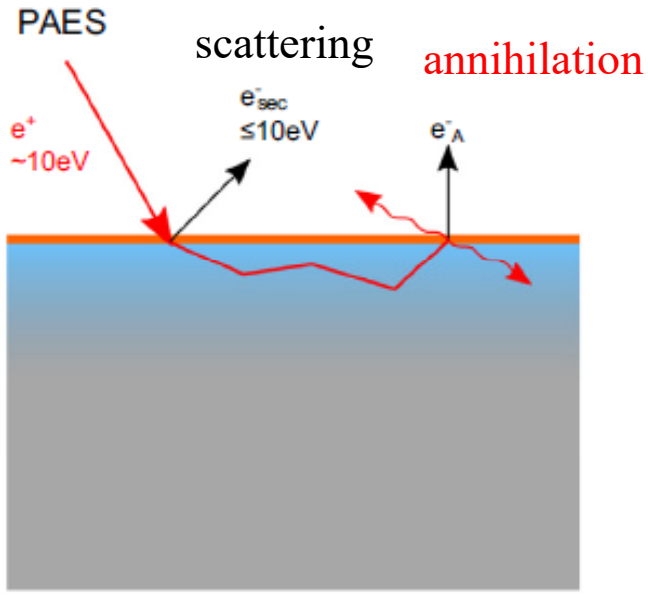


e^-_A – Auger electron created by electron-electron collision

e^-_S – secondary electron ($E \leq 1$ keV)

- **positron induced Auger-electron spectroscopy (PAES)**

topmost layer ⟶



e^-_A – Auger electron created by positron-electron anihilation

e^-_S – secondary electron created by positron-electron collision ($E \leq 10$ keV)

Positron induced Auger-electron spectroscopy (PAES)

- **core annihilation probability**

$$p_{core} = \pi r_0^2 c \int |\Psi_+(\vec{r})|^2 \sum_i |\Psi_i(\vec{r})|^2 \, d^3\vec{r}$$

classical e⁻ radius

e⁺ wave function

wave function of e⁻ in *i*-th level

number of e⁻ in given level

approximate formula: $p_{core} \approx \frac{6N(E_B)}{E_B^{1.6}}$

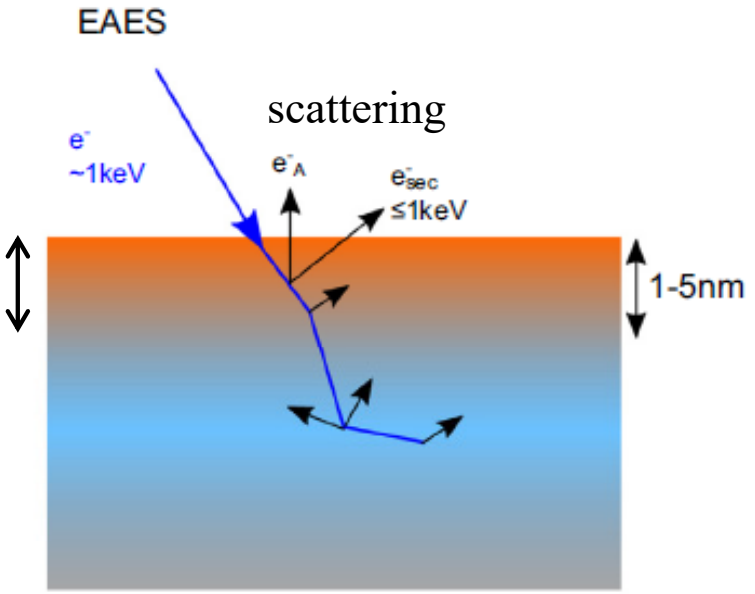
e⁻ binding energy in eV

Element	λ (ns^{-1})	Core-annihilation probabilities (%) Level: 1*s*	2*s*	2*p*	3*s*	3*p*
$_{3}$Li	3.45	5.42				
$_{4}$Be	7.04	4.37				
$_{11}$Na	2.96	0.049	2.11	6.86		
$_{12}$Mg	4.44	0.032	1.56	4.87		
$_{13}$Al	6.13	0.021	1.18	3.53		
$_{19}$K	2.52		0.028	0.069	1.27	5.25
$_{22}$Ti	6.80		0.045	0.11	2.31	8.70
$_{23}$V	7.69		0.053	0.12	2.76	10.21
$_{24}$Cr	8.33		0.059	0.14	3.07	11.28
$_{26}$Fe	9.43		0.034	0.076	1.98	7.20
$_{28}$Ni	9.09		0.034	0.075	2.07	7.41
$_{29}$Cu	9.09		0.027	0.058	1.66	5.93
$_{30}$Zn	6.76		0.018	0.038	1.18	4.23

Positron induced Auger-electron spectroscopy (PAES)

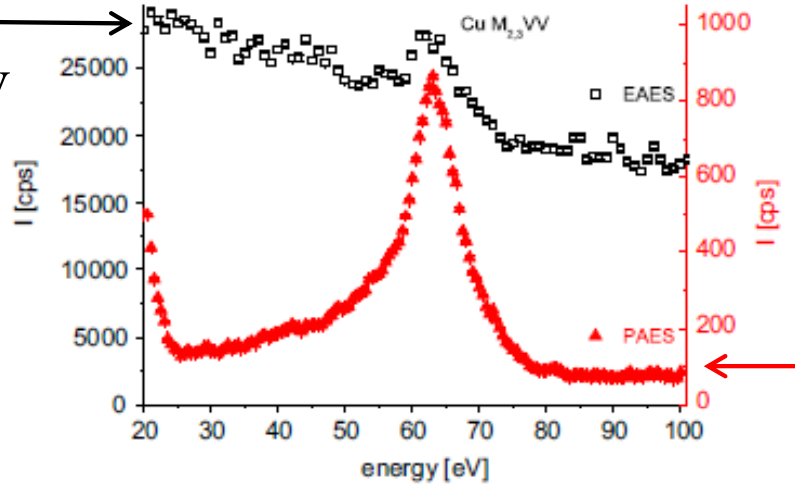
- **EAES and PAES comparison**

Method	EAES	PAES
Current	$I_{e^-} > \mu A$	$I_{e^+} < pA$
Setup	Simple	Elaborate
Beam energy	$\approx$ keV	≈ 20 eV
e^- background	High	"Zero"
Information depth	Several at. layers	Topmost at. layer
Auger yield (relative to EAES)	1	> 100
SNR (relative to EAES)	1	> 20

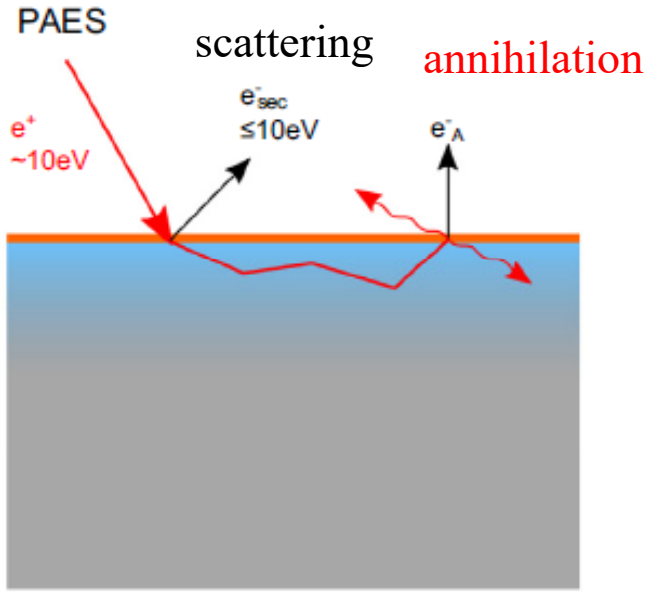


- **example pure Cu**

EAES
$E_- = 20$ keV



PAES
$E_+ = 2$ eV



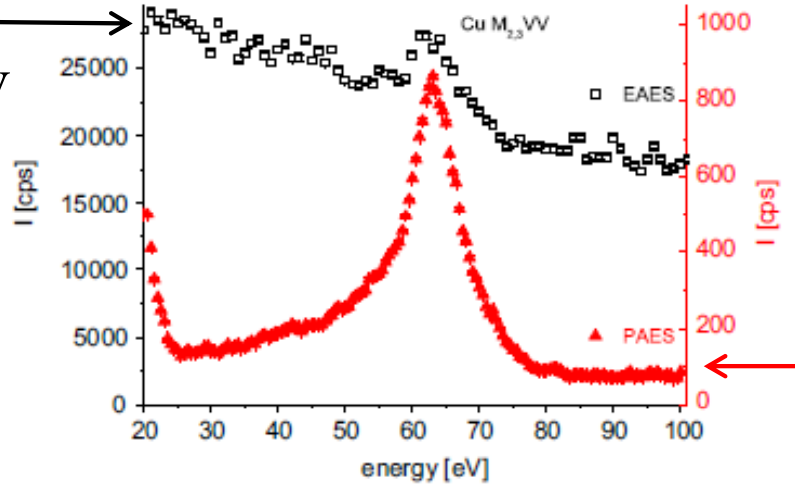
Positron induced Auger-electron spectroscopy (PAES)

- **EAES and PAES comparison**

Method	EAES	PAES
Current	$I_{e^-} > \mu A$	$I_{e^+} < pA$
Setup	Simple	Elaborate
Beam energy	≈ keV	≈ 20 eV
e^- background	High	"Zero"
Information depth	Several at. layers	Topmost at. layer
Auger yield (relative to EAES)	1	> 100
SNR (relative to EAES)	1	> 20

- **example pure Cu**

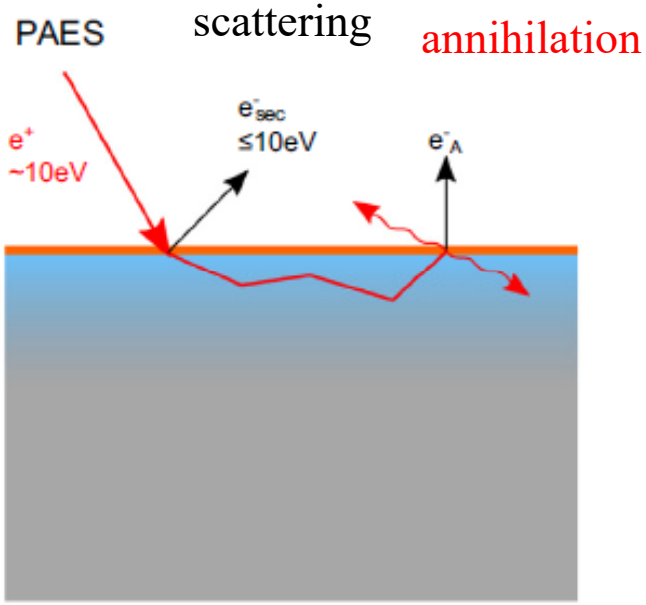
EAES →
$E_- = 20$ keV



← PAES
$E_+ = 2$ eV

- **PAES advantages**

- **surface sensitivity**
  topmost layer
- **Auger electron yield**
  N_A/N_{inc} two orders of magnitude higher compared to EAES
- **zero electron background**
  signal-to-noise ratio (SNR)
  EAES SNR = 1:2
  PAES SNR = 10:1



Positron induced Auger-electron spectroscopy (PAES)

- **positron induced Auger-electron spectroscopy (PAES)**

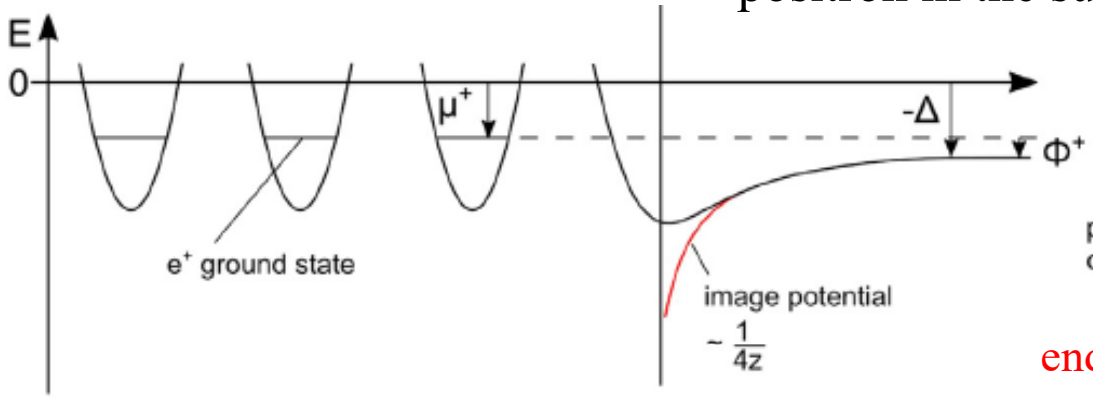
- energy of secondary electron

$$E_- \leq E_+ + \phi_+ - \phi_-$$

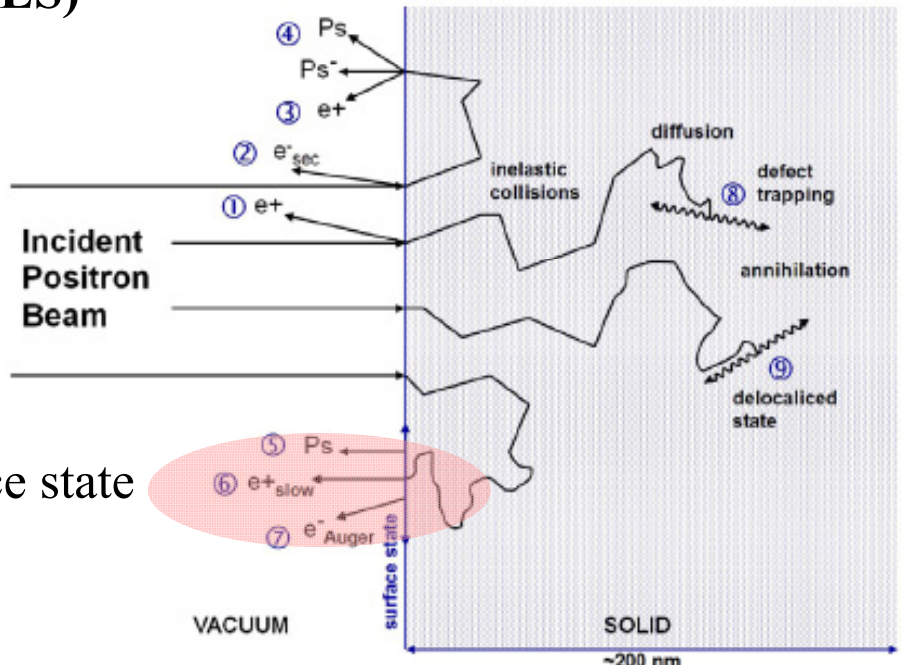
energy of incident e^+

e^+ work-function

e^- work-function



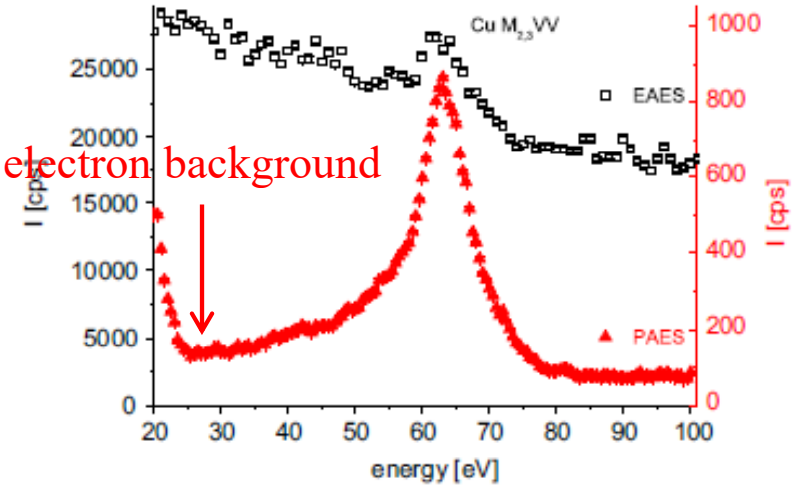
positron in the surface state



positrons: $\Phi^+ = -\Delta - \mu^+$

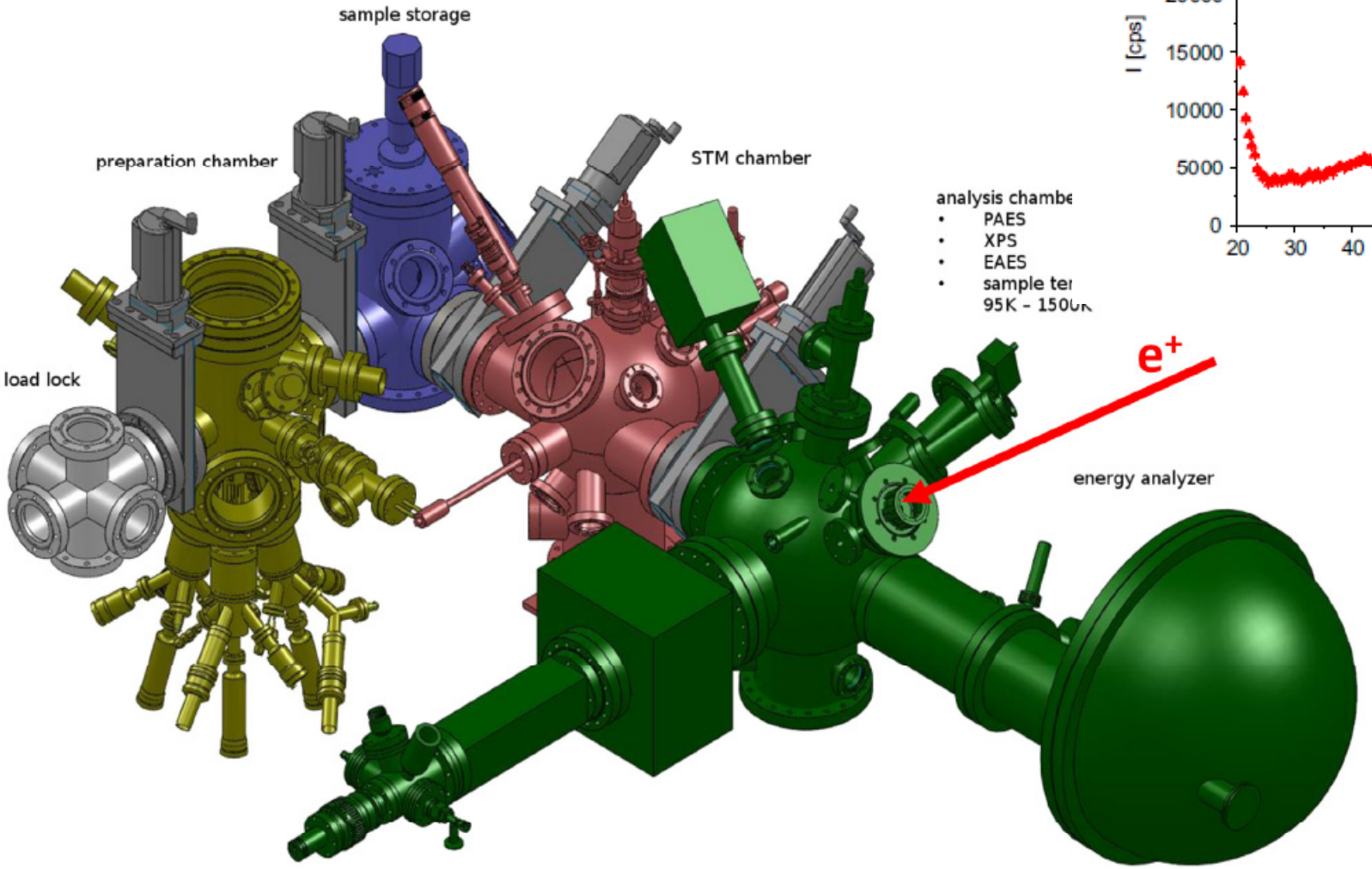
Φ^+ can be <0 !

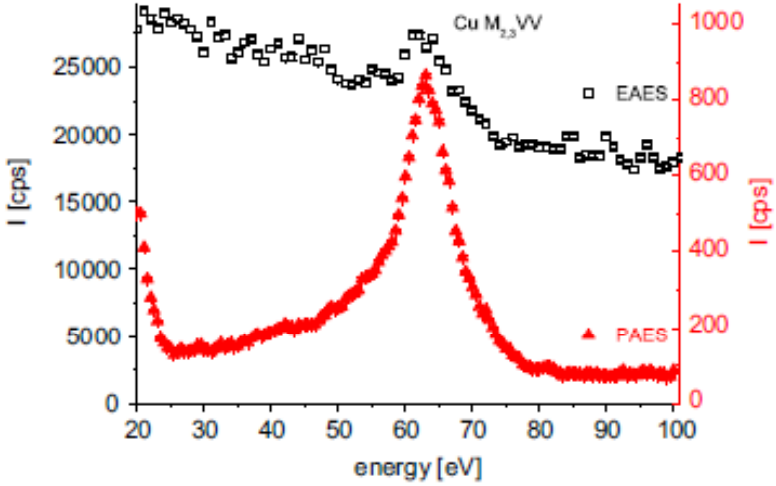
end of secondary electron background



Positron induced Auger-electron spectroscopy (PAES)

- **PAES spectrometer at NEPOMUC**

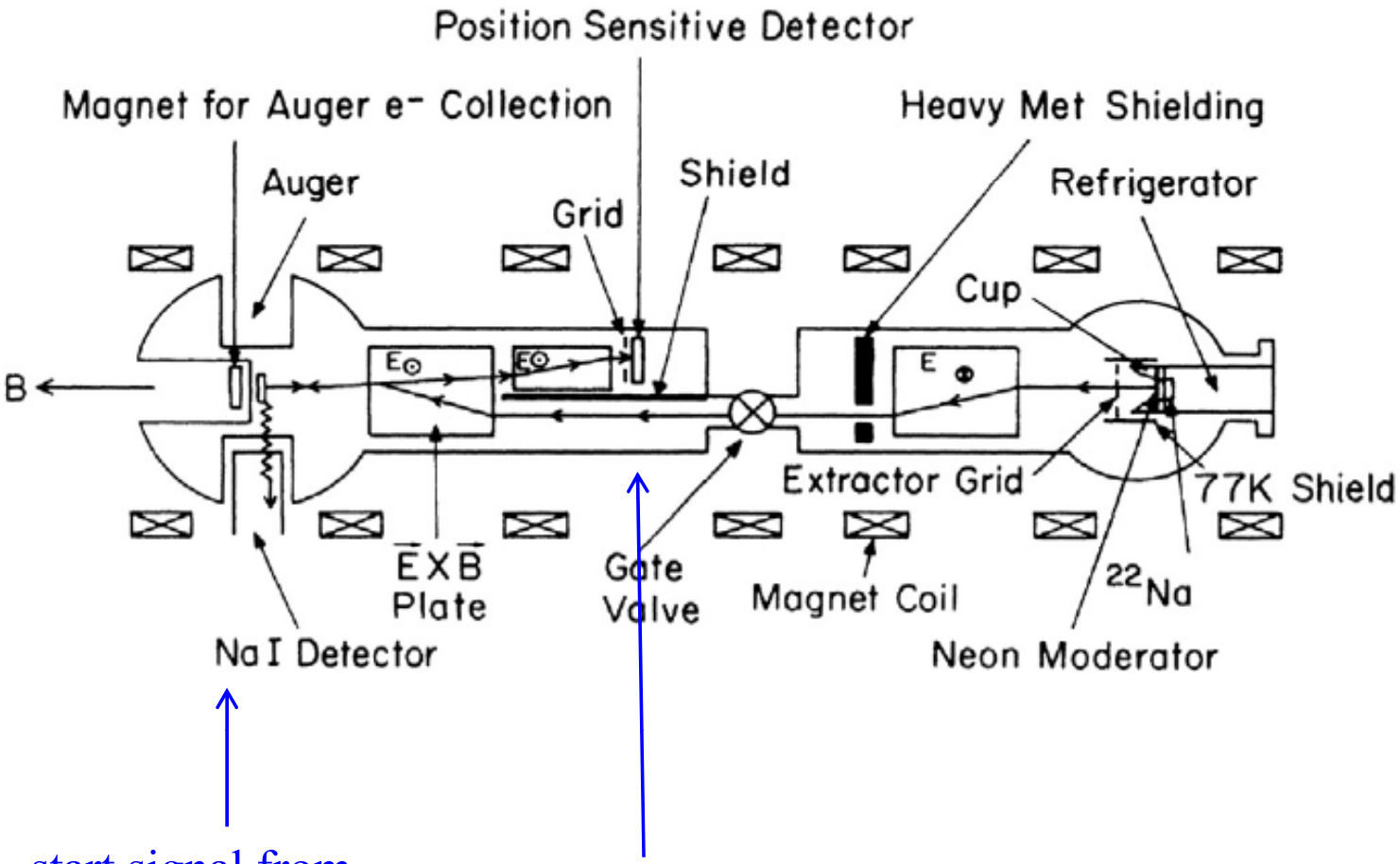




hemispherical electron energy analyzer

Positron induced Auger-electron spectroscopy (PAES)

- **Time of flight (TOF-PAES) spectrometer at NEPOMUC**

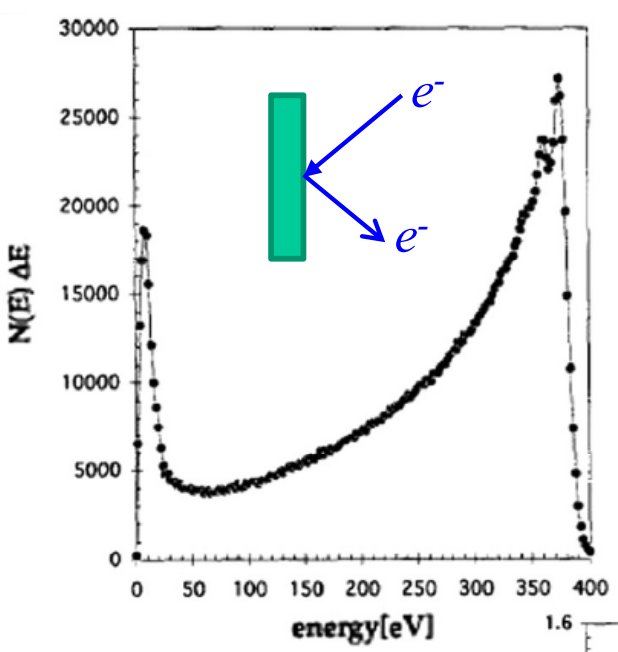


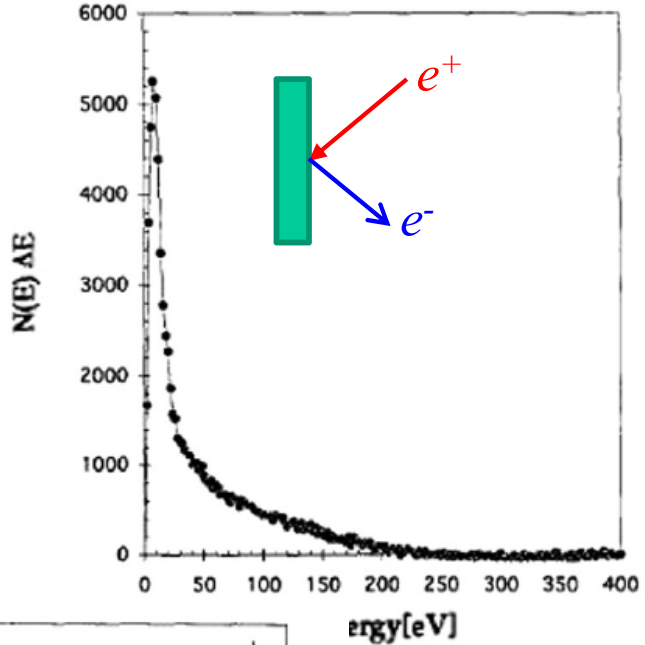
start signal from
511 keV annihilation
gamma ray

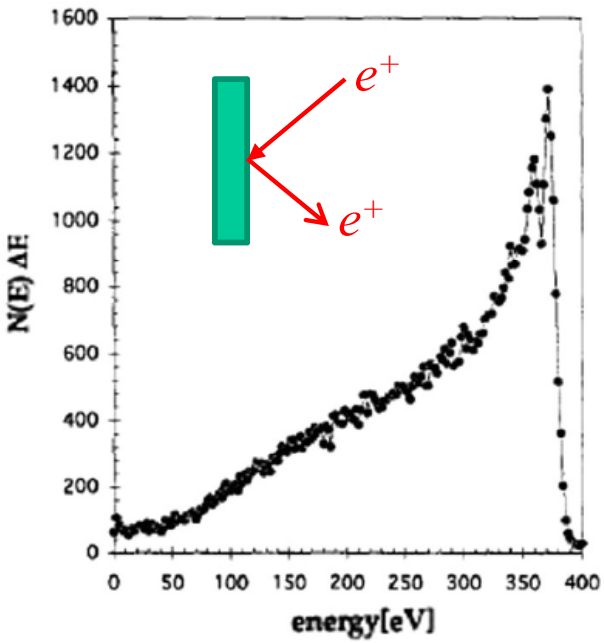
stop signal from Auger electrons passed retarding flight tube

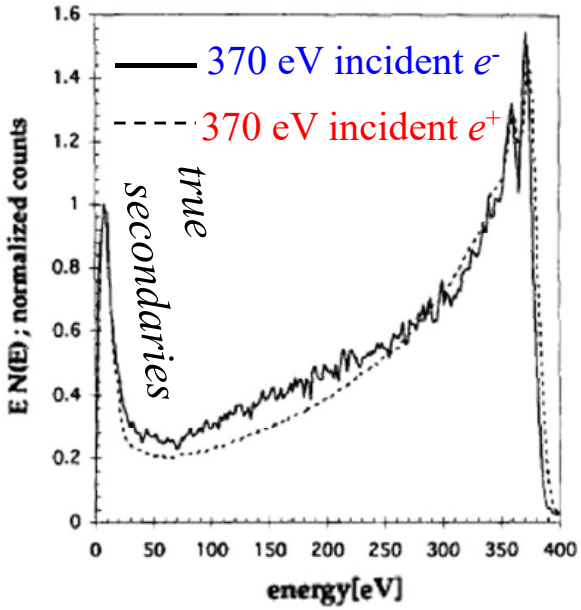
Positron induced Auger-electron spectroscopy (PAES)

positrons and electrons emitted from Ge (100) surface bombarded by 370 eV electrons and positrons



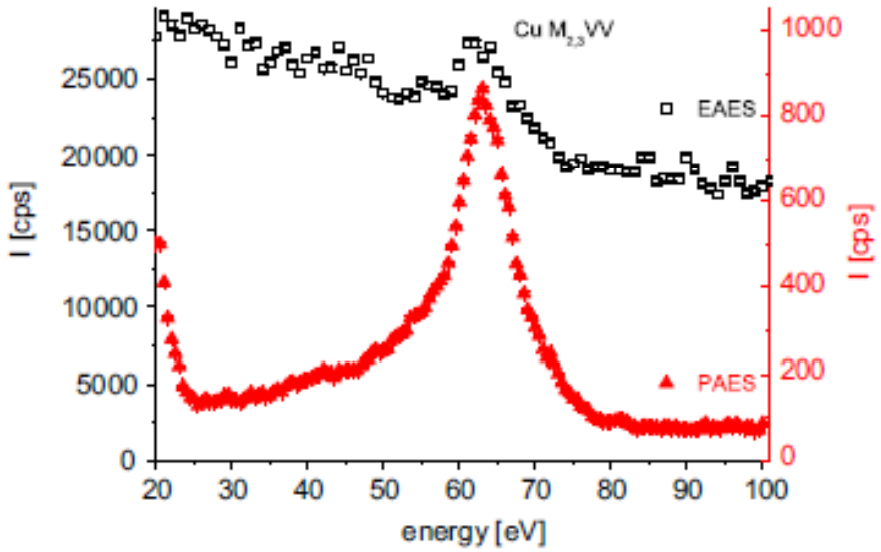




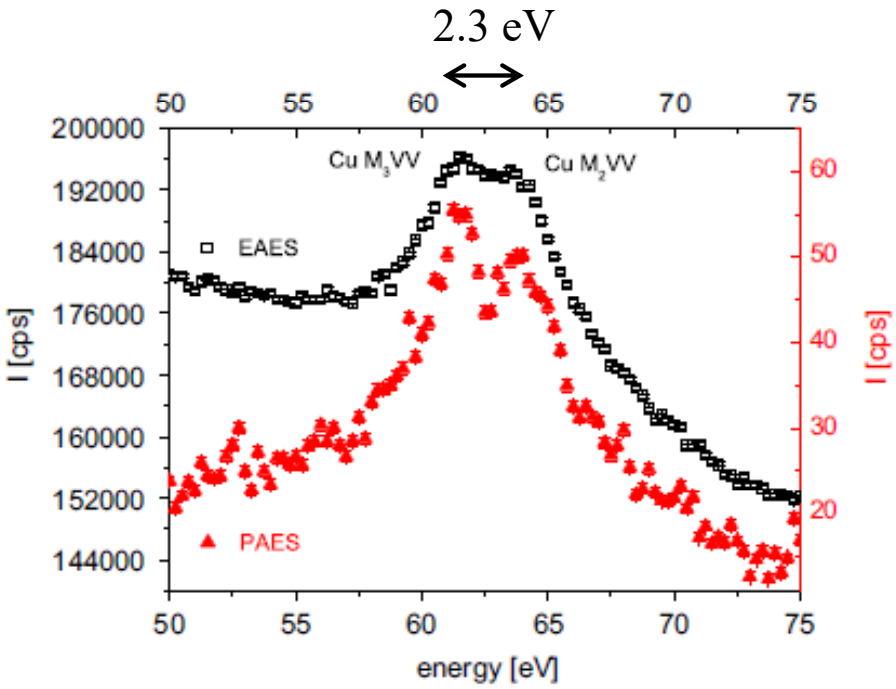


Positron induced Auger-electron spectroscopy (PAES)

- **EAES and PAES on polycrystalline Cu surface**



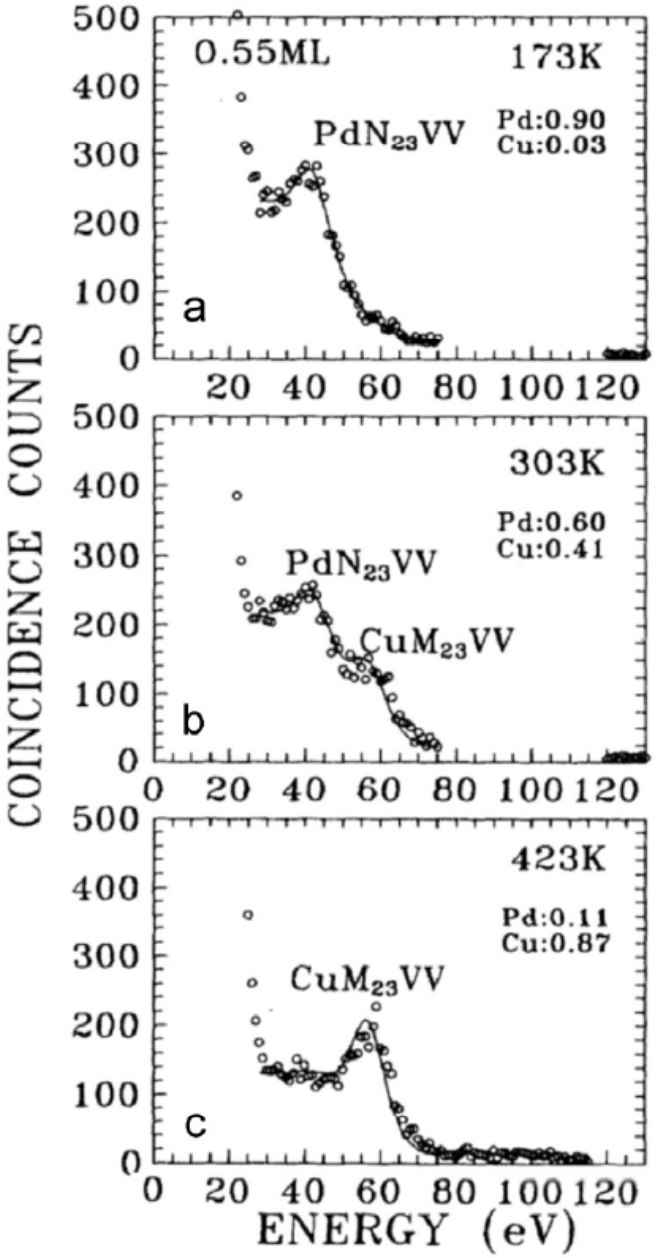
higher resolution Auger-electron analyzer



Positron induced Auger-electron spectroscopy (PAES)

- **PAES on polycrystalline Cu (100) surface covered with 0.55 ML Pd**

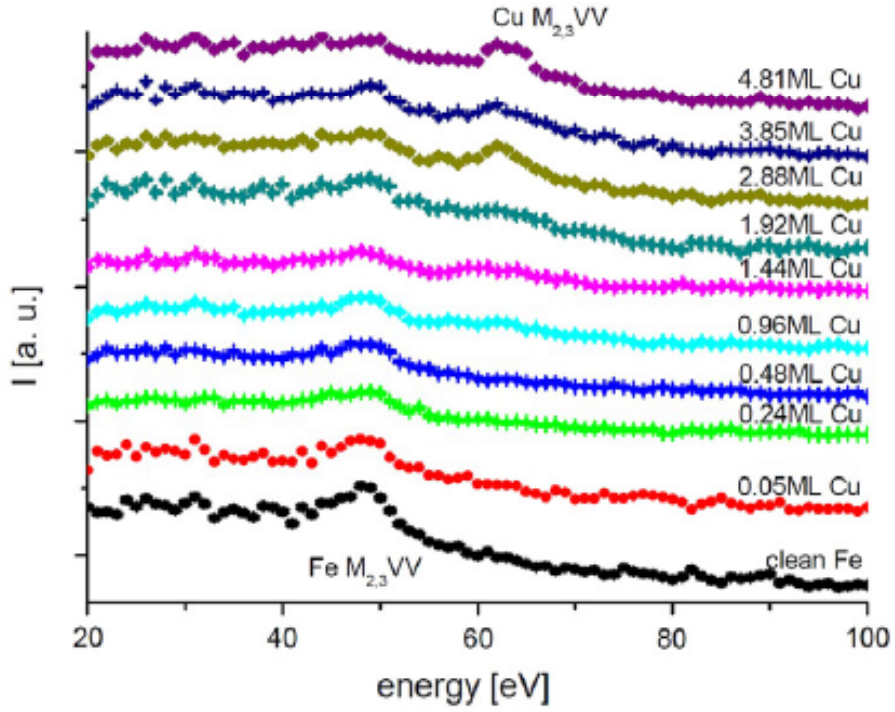
surface alloying of Pd with Cu at 150^{o}C



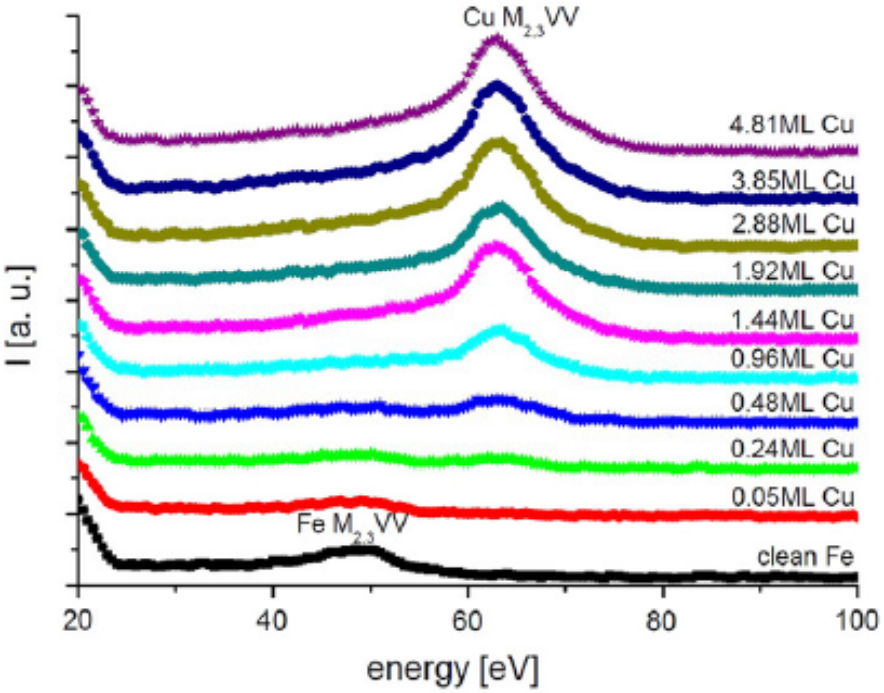
Positron induced Auger-electron spectroscopy (PAES)

- **Fe covered with Cu**

EAES



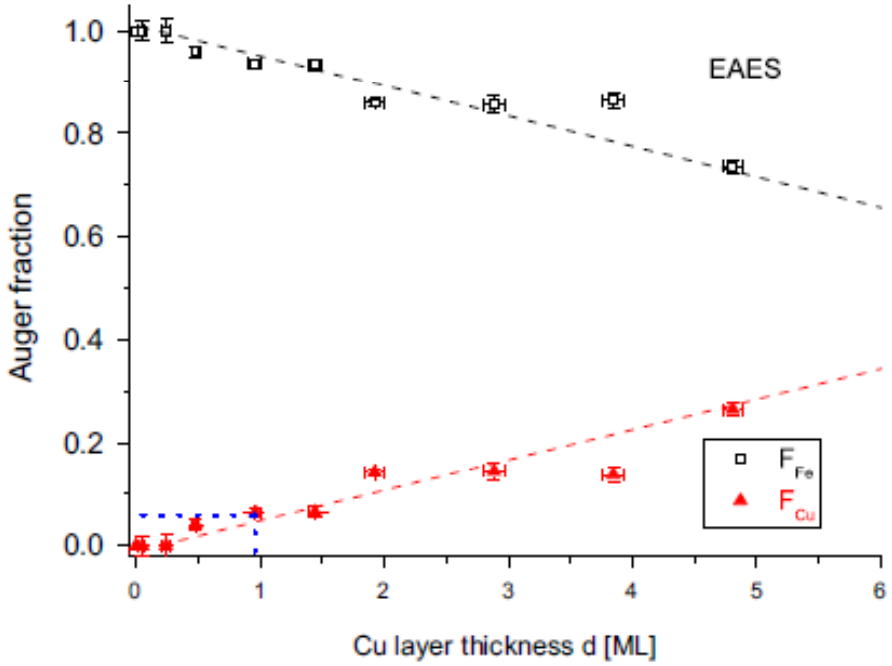
PAES



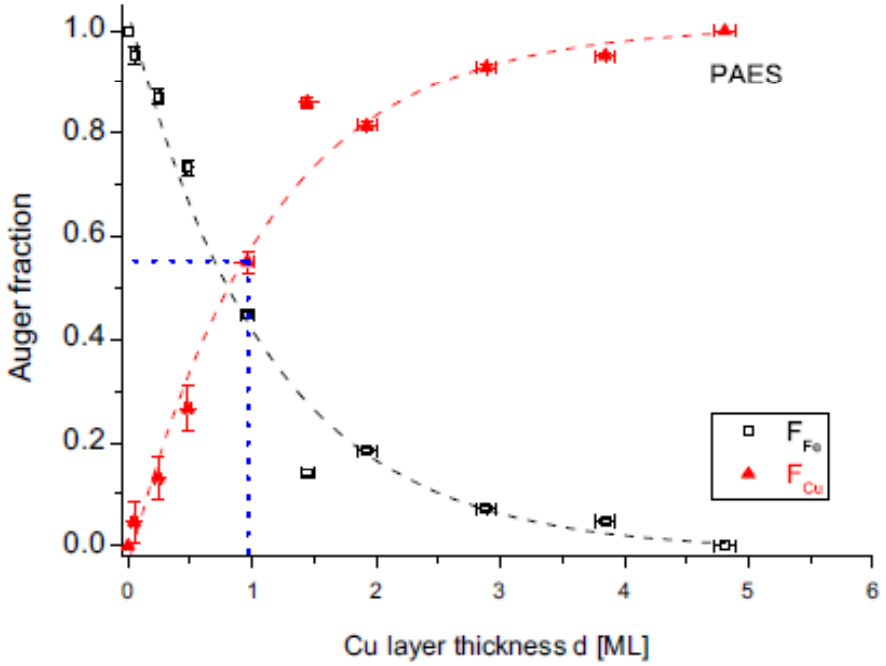
Positron induced Auger-electron spectroscopy (PAES)

- **Fe covered with Cu**

EAES



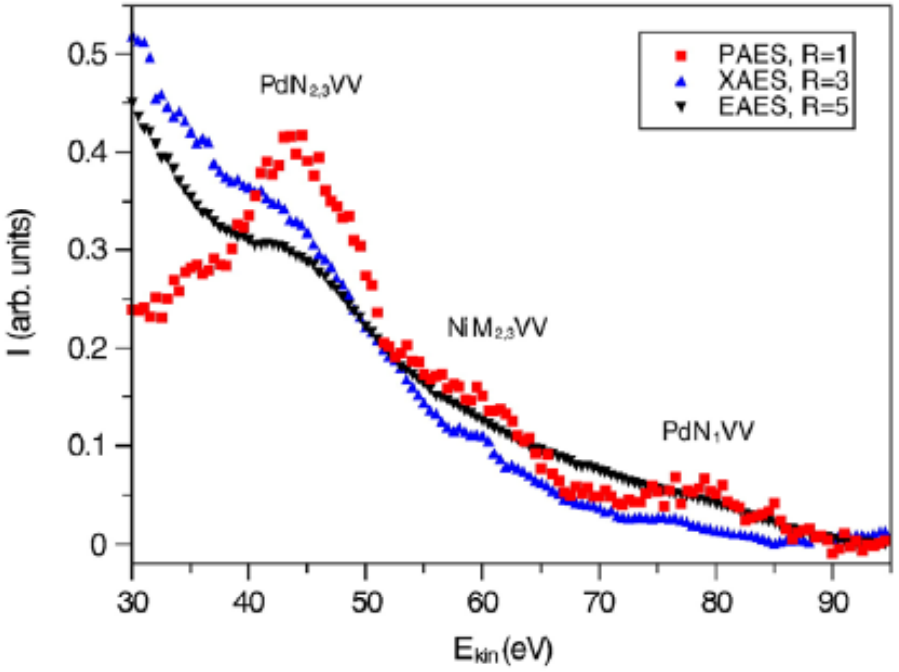
PAES



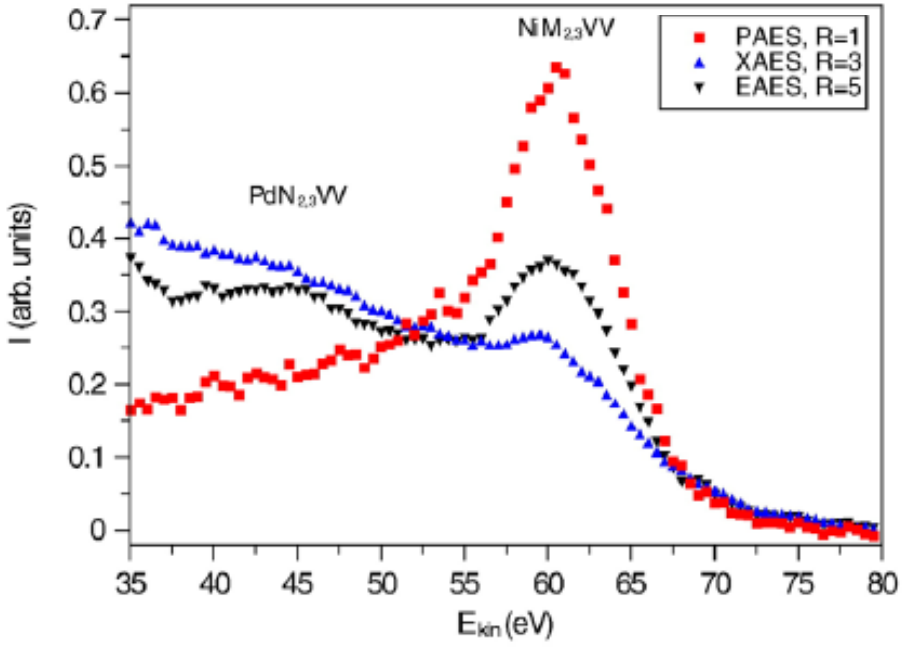
Positron induced Auger-electron spectroscopy (PAES)

- **Pd covered with Ni**

0.1 ML Ni

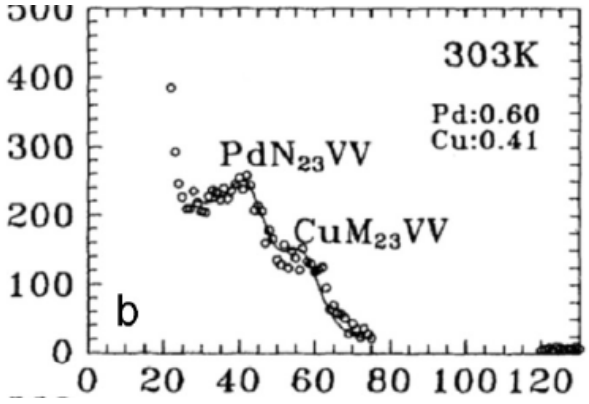


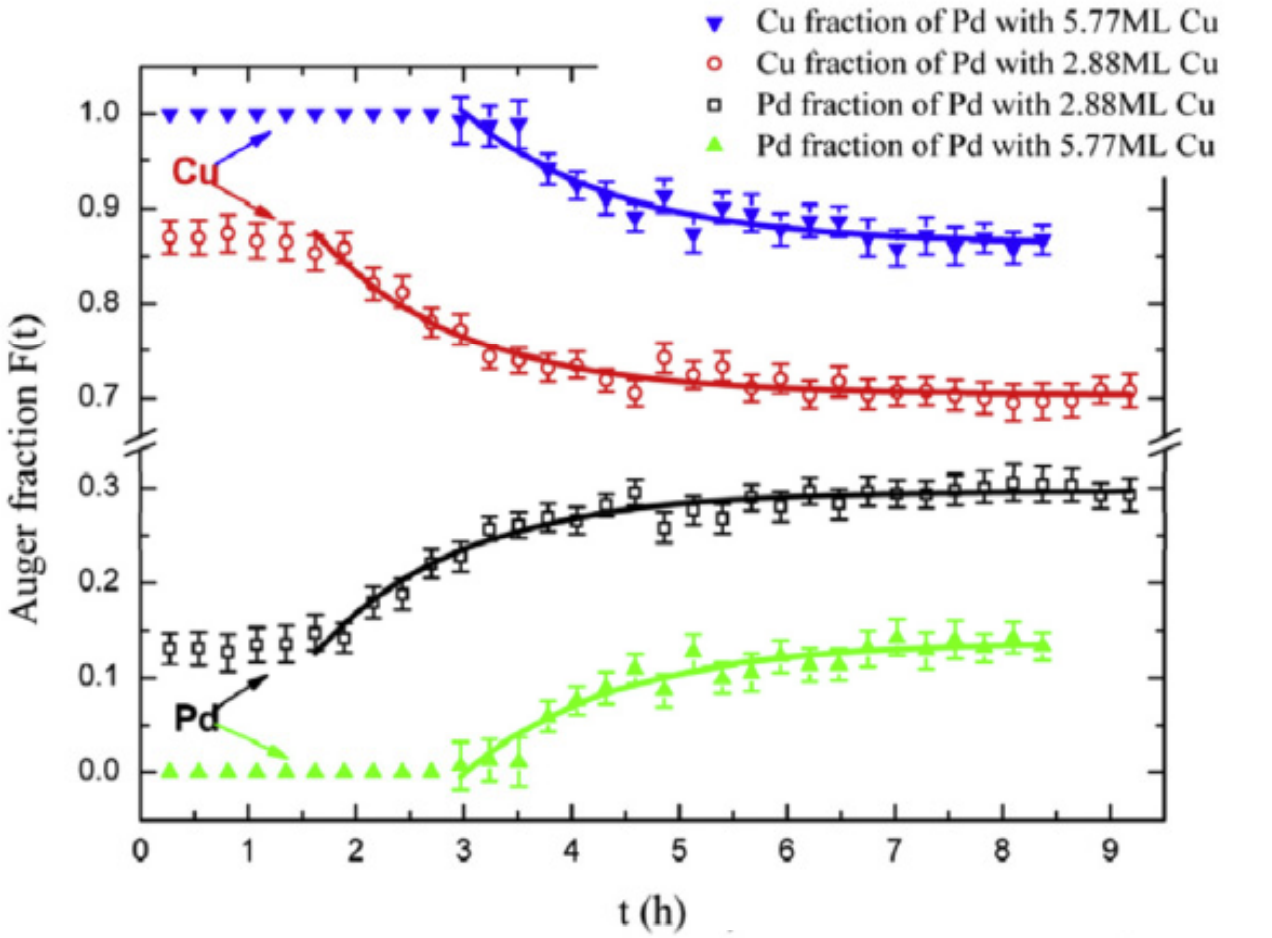
1 ML Ni

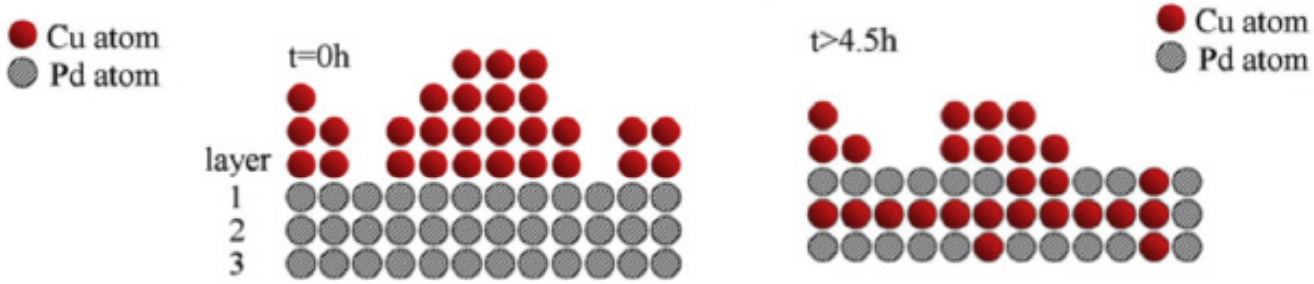


Positron induced Auger-electron spectroscopy (PAES)

- time dependent PAES
- Cu on Pd

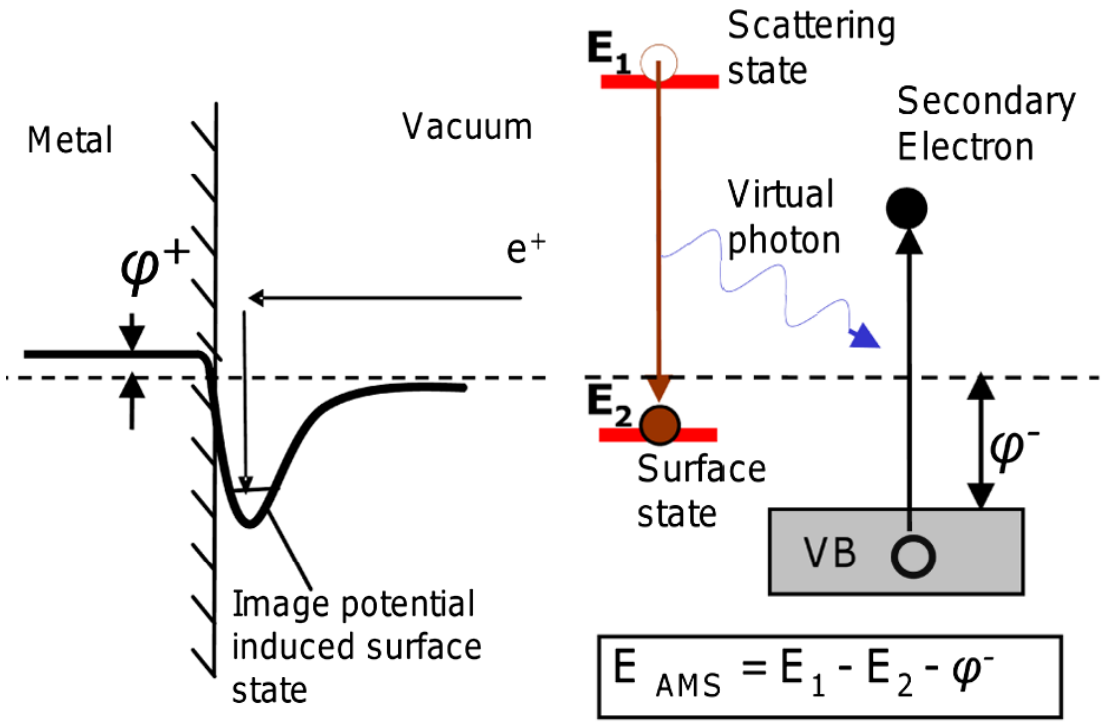






Positron induced Auger-electron spectroscopy (PAES)

- **Auger-mediated sticking (AMS)**



- de Broglie wavelength of 1 keV positron is ≈ 12 Å
- order of magnitude higher than the width of surface potential well

Positron induced Auger-electron spectroscopy (PAES)

- **Auger-mediated sticking (AMS)**
- **Cu sample**
- bulk process

$E_{max} = E_+ - \phi_- + \phi_+$

E_+: energy of incident e^+

ϕ_-: e^- work-function

ϕ_+: e^+ work-function

- Cu:

$\phi_- = 4.65$ eV

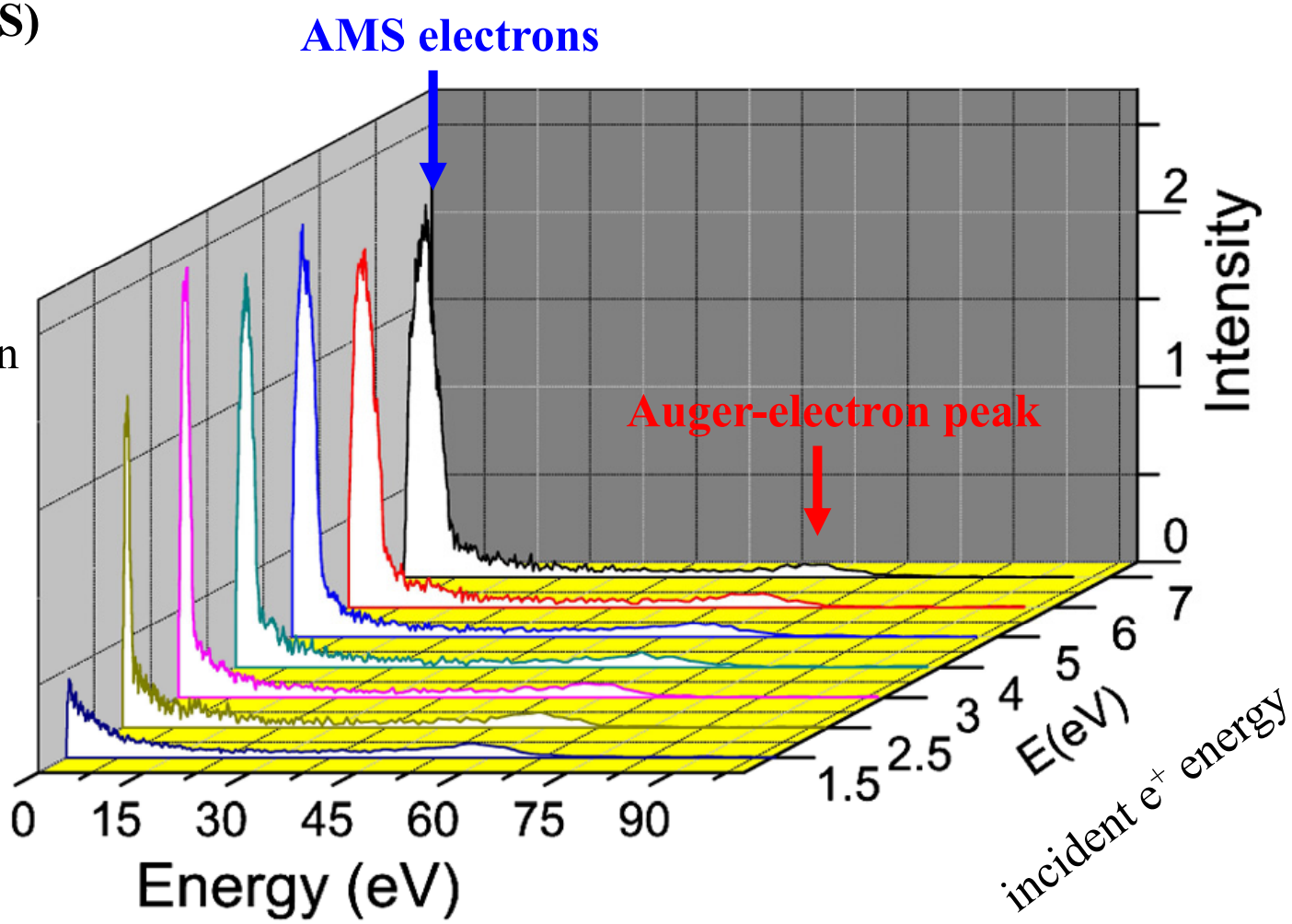
$\phi_+ = -0.02$ eV

⇨ no emission below 4.7 eV

- AMS process

$E_{max} = E_+ - \phi_- + E_{ss}$

E_{ss}: e^+ binding energy to the surface



energy of detected e^-

Positron induced Auger-electron spectroscopy (PAES)

- **Auger-mediated sticking (AMS)**
- **Cu sample**
- bulk process

$$E_{max} = E_{+} - \phi_{-} + \phi_{\pm}$$

E_{+}: energy of incident e^+

ϕ_{-}: e^- work-function

$\phi_{\pm}$: e^+ work-function

- Cu:

$\phi_{-} = 4.65$ eV

$\phi_{+} = -0.02$ eV

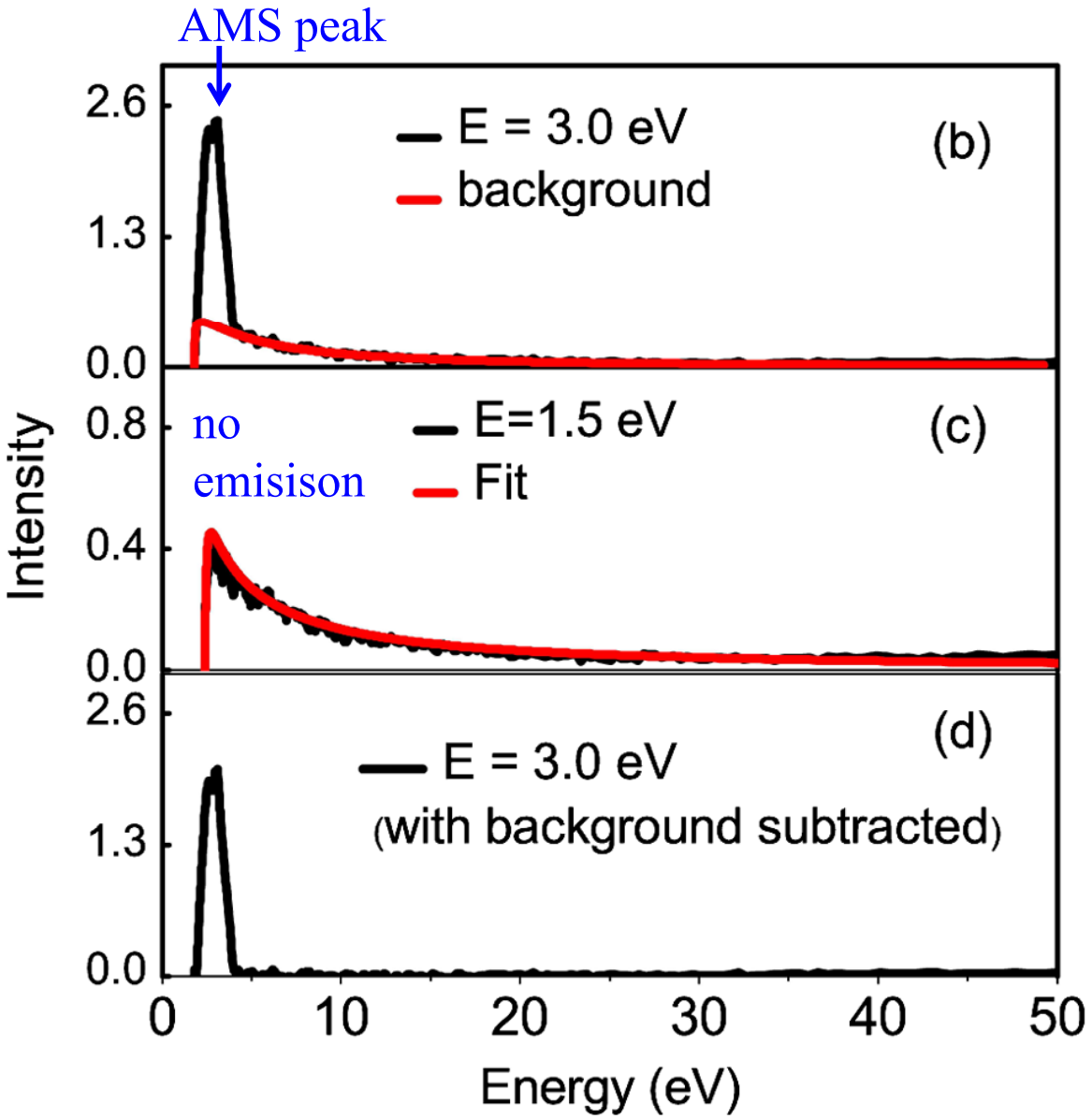
⇨ no emission below 4.7 eV

- AMS process

$$E_{max} = E_{+} - \phi_{-} + E_{ss}$$

E_{ss}: e^+ binding energy to the surface

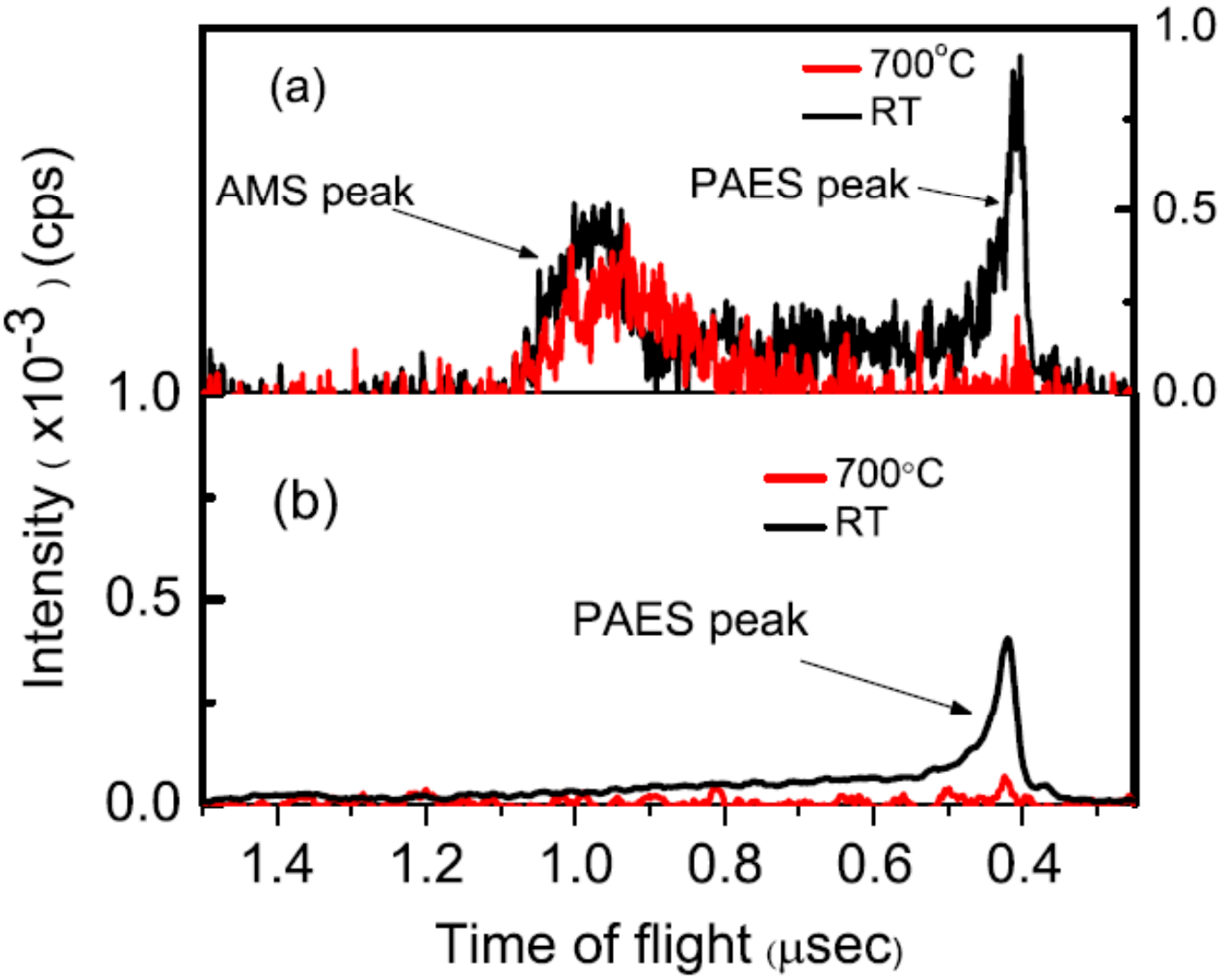
$E_{ss} > \phi_{+}$



Positron induced Auger-electron spectroscopy (PAES)

- **Auger-mediated sticking (AMS)**
- **Cu sample**
- PAES peak disappears due to thermally activated Ps desorption
- AMS peak remains

Effect of temperature



Positron induced Auger-electron spectroscopy (PAES)

- **Auger-mediated sticking (AMS)**
- **Cu and Au sample**
- bulk process

$E_{max} = E_{+} - \phi_{-} + \phi_{\pm}$

E_{+}: energy of incident e^{+}

ϕ_{-}: e^{-} work-function

$\phi_{\pm}$: e^{+} work-function

- Cu:

$\phi_{-} = 4.65$ eV

$\phi_{+} = -0.02$ eV

⇨ no emission below 4.7 eV

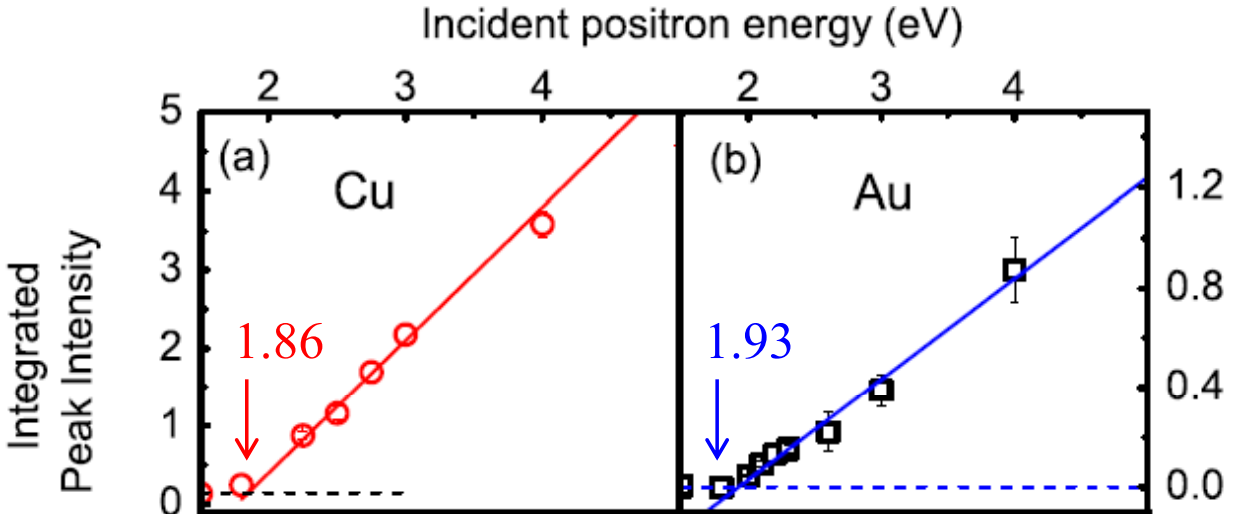
- AMS process

$E_{max} = E_{+} - \phi_{-} + E_{ss}$

E_{ss}: e^{+} binding energy to the surface

$E_{ss} > \phi_{+}$

Determination of E_{ss}



$E_{ss} = (2.79 \pm 0.2)$ eV $\quad E_{ss} = (2.87 \pm 0.2)$ eV

Cu:

$\phi_{-} = 4.65$ eV

$\phi_{+} = -0.02$ eV

Au:

$\phi_{-} = 4.8$ eV

$\phi_{+} = 0.9$ eV

Positron induced Auger-electron spectroscopy (PAES)

- **Auger-mediated sticking (AMS)**
- **Cu and Au sample**
- bulk process

$$E_{max} = E_{+} - \phi_{-} + \phi_{+}$$

energy of incident e^+

e^- work-function

e^+ work-function

- Cu:

$\phi_{-} = 4.65$ eV

$\phi_{+} = -0.02$ eV

⇨ no emission below 4.7 eV

- AMS process

$$E_{max} = E_{+} - \phi_{-} + E_{ss}$$

e^+ binding energy to the surface

$E_{ss} > \phi_{+}$

Determination of E_{ss}