Evidence of Ultrashort Orbital Transport in Heavy Metals Revealed by Terahertz Emission Spectroscopy

WU GROUP

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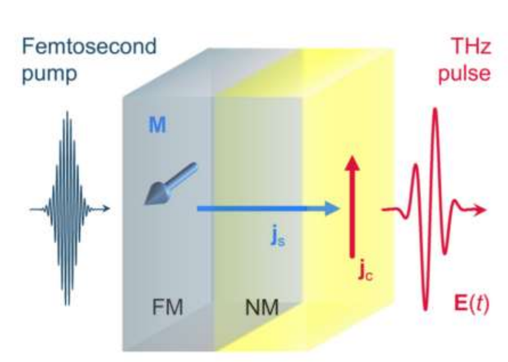
Motivation

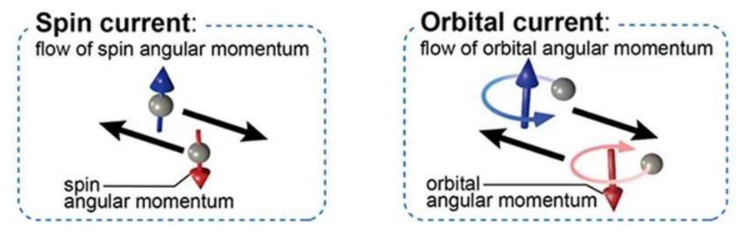
Spintronic Terahertz Emission



- ✓Broadband THz radiation
- ✓High electric-field amplitude
- ✓Magnetically tunable polarization
- ✓Ultrafast dynamics information

Promising and powerful

Orbital Current J_L



Orbital relaxation length from first-principles scattering calculations

Max Rang and Paul J. Kelly

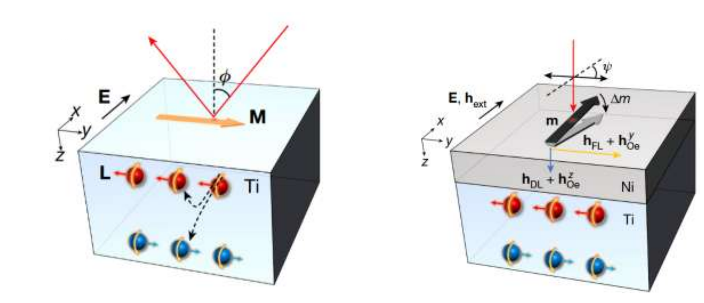
Faculty of Science and Technology and MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

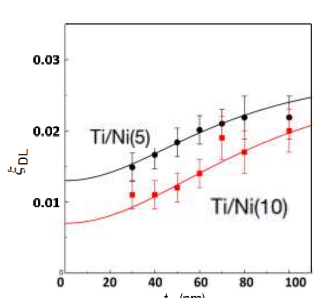
	l/e at layer No.	d (nm) per atomic layer	l_{ol} (nm)
Pt	3	0.23	0.6
Cu	2	0.21	0.4
V	3	0.14	0.5
Cr	2–5	0.15	0.3–0.8

M. Rang, *et al.*, Phys. Rev. B **109**, 214427 (2024).

Small λ_L from calculation

Experimental measurement of J_L





Orbital hall effect in Ti

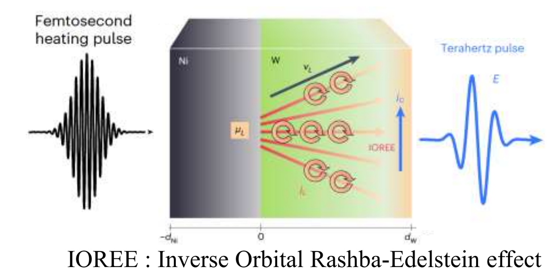
$J_L \to J_c$

$\lambda_L = 50 \pm 15$nm

Y.-G. Choi, *et al.*, Nature **619**, 52 (2023).

Large λ_L in LM from experiments → λ_L in Heavy metals(HM)?

J_L-induced THz Emission in Ni/W



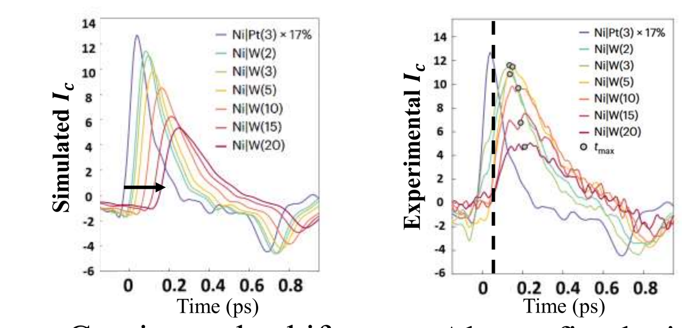
W|SiO$_2$ interface

$J_L \to J_c$

λ_L~80nm

IOREE : Inverse Orbital Rashba-Edelstein effect

T. S. Seifert, *et al.*, Nat. Nanotechnol. **18**, 1132 (2023).



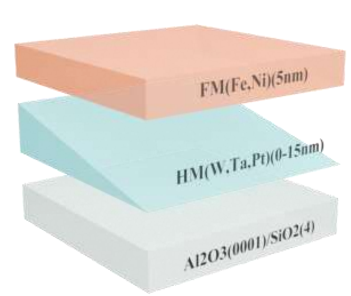
Continuously shift with d_W

Almost fixed with $d_W > 5$nm

THz emission mechanism in Ni/W?

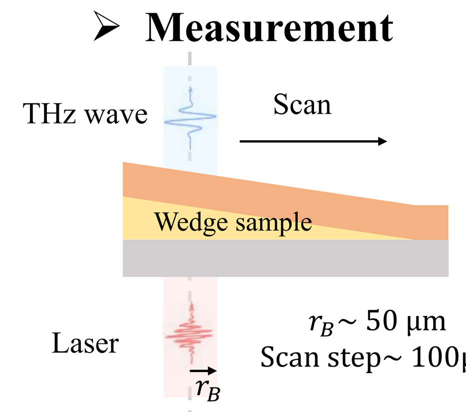
Sample Preparation and Measurement

➢ **Sample Structure**



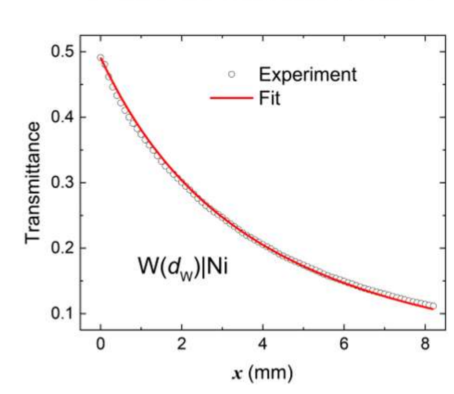
HM(W, Ta, Pt) wedge samples

➢ **Measurement**



Scan along wedge direction

➢ **NIR Transmittance**

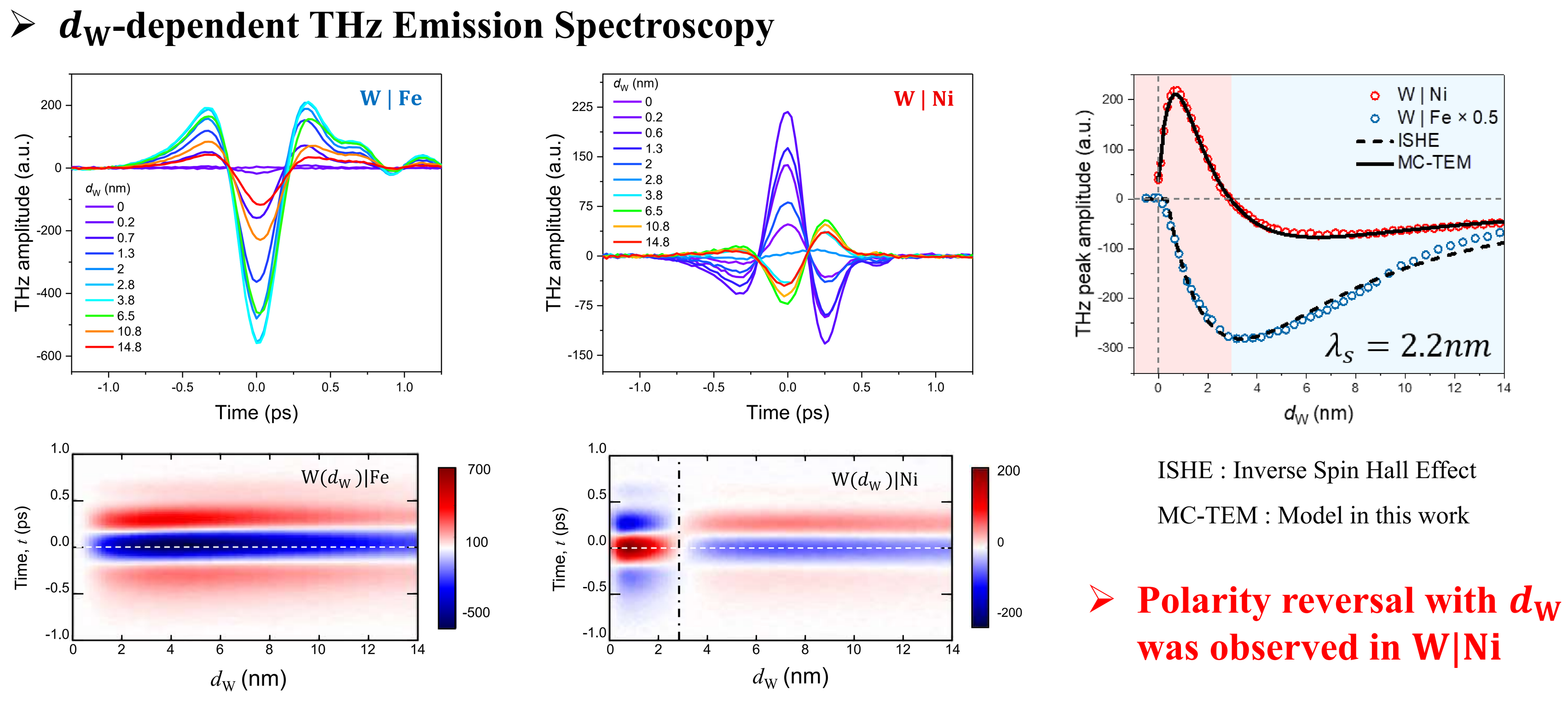


Film thickness verification

High-resolution thickness-dependent measurement on one wedge sample

d_W-dependent Polarity Reversal

➢ **d_W-dependent THz Emission Spectroscopy**



ISHE : Inverse Spin Hall Effect

MC-TEM : Model in this work

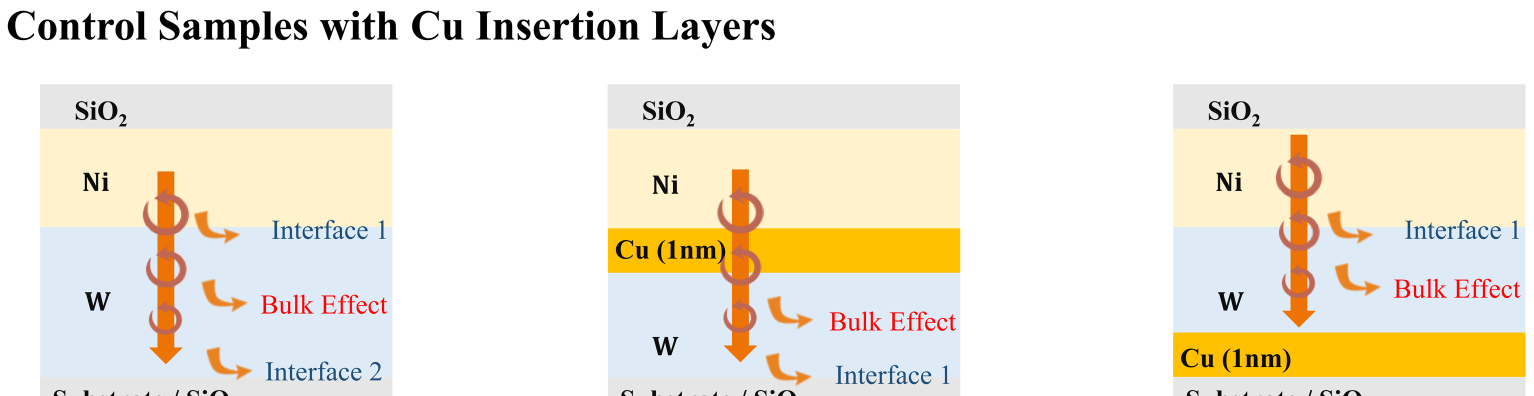
➢ **Polarity reversal with d_W was observed in W|Ni**

➢ **Laser-pumped orbital currents J_L in Ni**

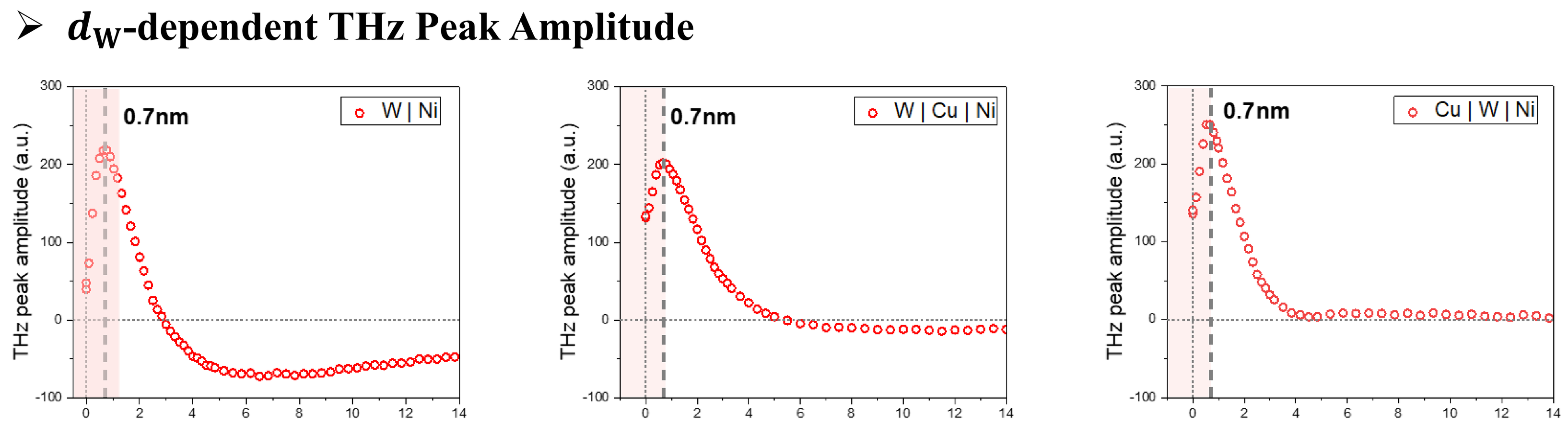
- W|Fe : THz spectroscopy agrees well with ISHE THz emission model → $\lambda_s = 2.2$nm
- W|Ni : Opposite polarity to W|Fe with $d_W < 2$nm → origins from J_L in Ni

Ruling Out Interfacial Effects

➢ **Control Samples with Cu Insertion Layers**



➢ **d_W-dependent THz Peak Amplitude**



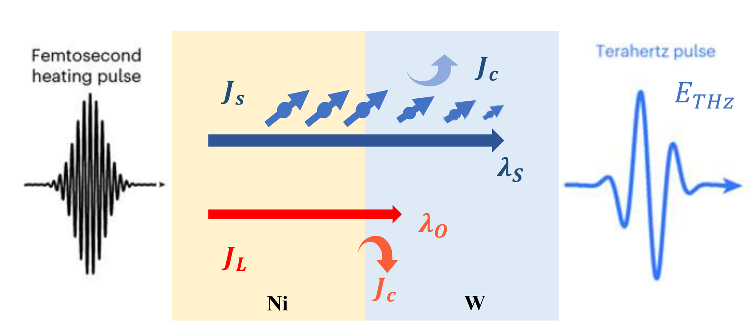
Rapid THz signal increase with d_W (< 0.7nm) remains consistent

× Interfacial effect(IOREE…) ✓Bulk conversion(IOHE)

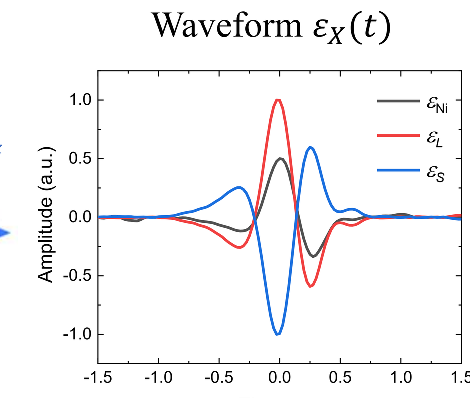
Multi-component THz Emission Model

➢ **Multi-component THz Emission Model (MC-TEM)**

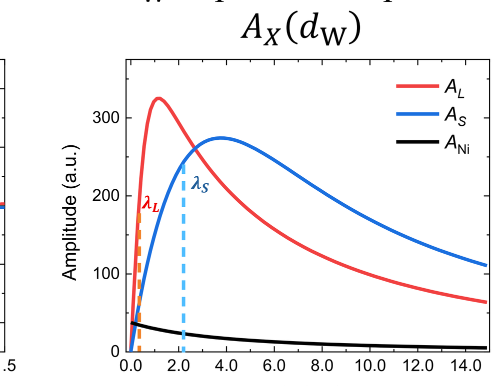
Multi-component in total E_{THz}



Waveform $\varepsilon_X(t)$



d_W-dependent amplitude $A_X(d_W)$



$E_{THz} = E_S + E_L + E_{Ni}$

E_S : ISHE E_L : IOHE

E_{Ni} : MDE + AHE ⋯

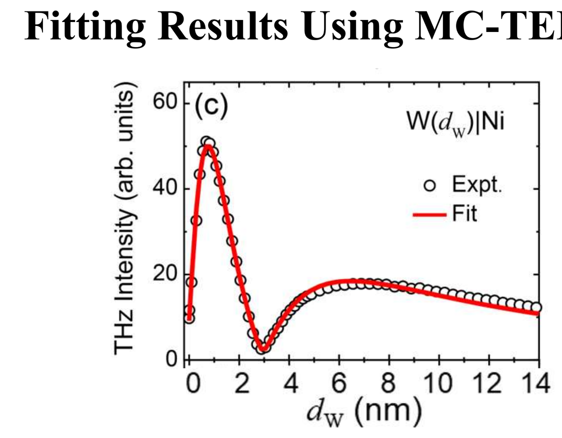
$E_X = A_X(d_W) \cdot \varepsilon_X(t)$ $(E_X \to E_S, E_L, E_{Ni})$

Experimental data → $\varepsilon_X(t)$ $\tilde{A}_S, \tilde{A}_L, \lambda_S, \lambda_L \to A_X(d_W)$

$E_{THz} = \sum_X A_X(d_W) \cdot \varepsilon_X(t) \to$ fit experimental data

$\tilde{A}_S, \tilde{A}_L, \lambda_S, \lambda_L$

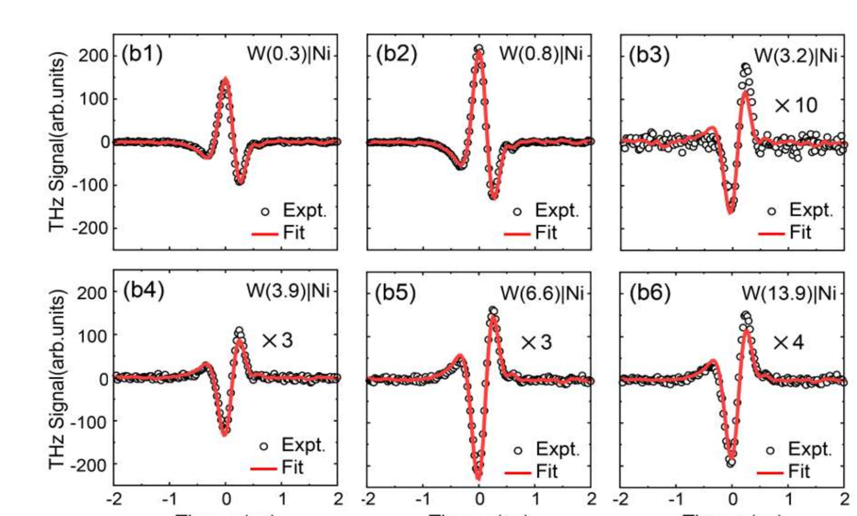
➢ **Fitting Results Using MC-TEM**



$\lambda_L = 0.36 \pm 0.17$ nm

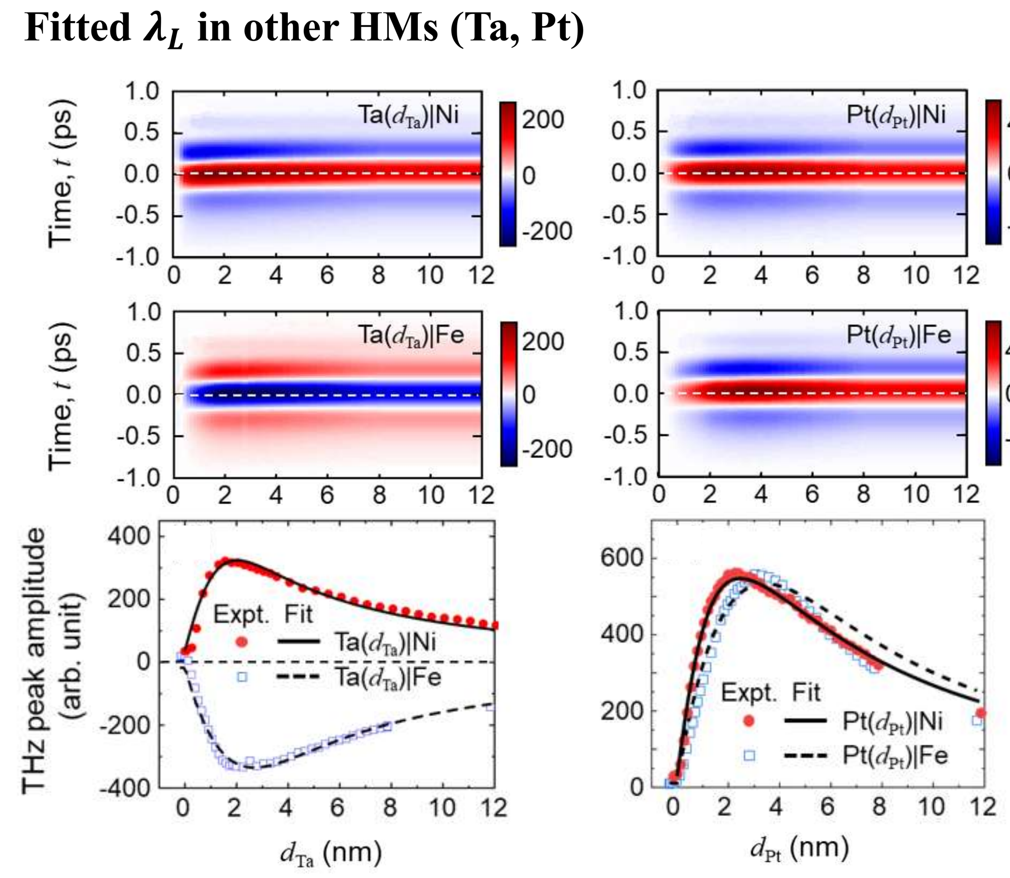
$\lambda_s = 2.20 \pm 0.13$ nm

Fitted λ_L is extremely short in W!



Fitting results agree well with experimental data

➢ **Fitted λ_L in other HMs (Ta, Pt)**

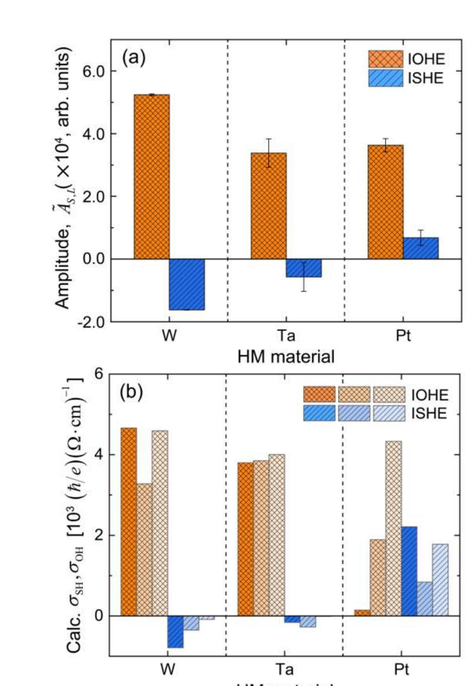


$\lambda_L = 0.84 \pm 0.51$ nm

$\lambda_s = 1.34 \pm 0.07$ nm

$\lambda_L = 0.94 \pm 0.44$ nm

$\lambda_s = 2.00 \pm 0.34$ nm



- The signs of $\tilde{A}_S, \tilde{A}_L$ are consistent with theoretical σ_{SH} and σ_{OH}.
- **Ultrashort fitted λ_L(<1nm) in heavy metals !**

Conclusion

Ultrashort orbital transport in Heavy metals

➢Multi-component THz emission spectroscopy was observed in HMs/Ni.

➢Interfacial conversion mechanisms are ruled out.

➢Experimental data show excellent agreement with the MC-TEM.

➢Ultrashort λ_L is revealed in HMs.

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Nat. Nanotechnol. 21, 538–545 (2026).