



UNIVERSITY OF
CAMBRIDGE

Ultra-fast readout of a ferromagnet and anti-ferromagnet

Chiara Ciccarelli

Mainz, October 2018

EXPERIMENT 1

Element-selective spin emission from a
ferrimagnet

Rare earth-transition metals alloys

Periodic Table of the Elements

Element symbol represents state at room temperature.

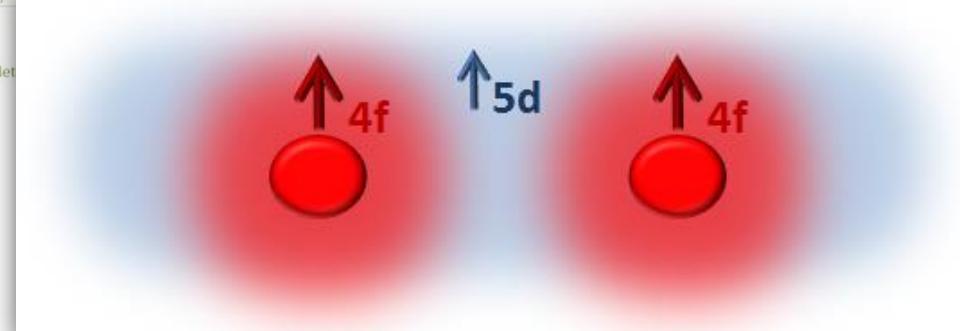
Solid, Liquid or Gas

Periodic Table Legend:

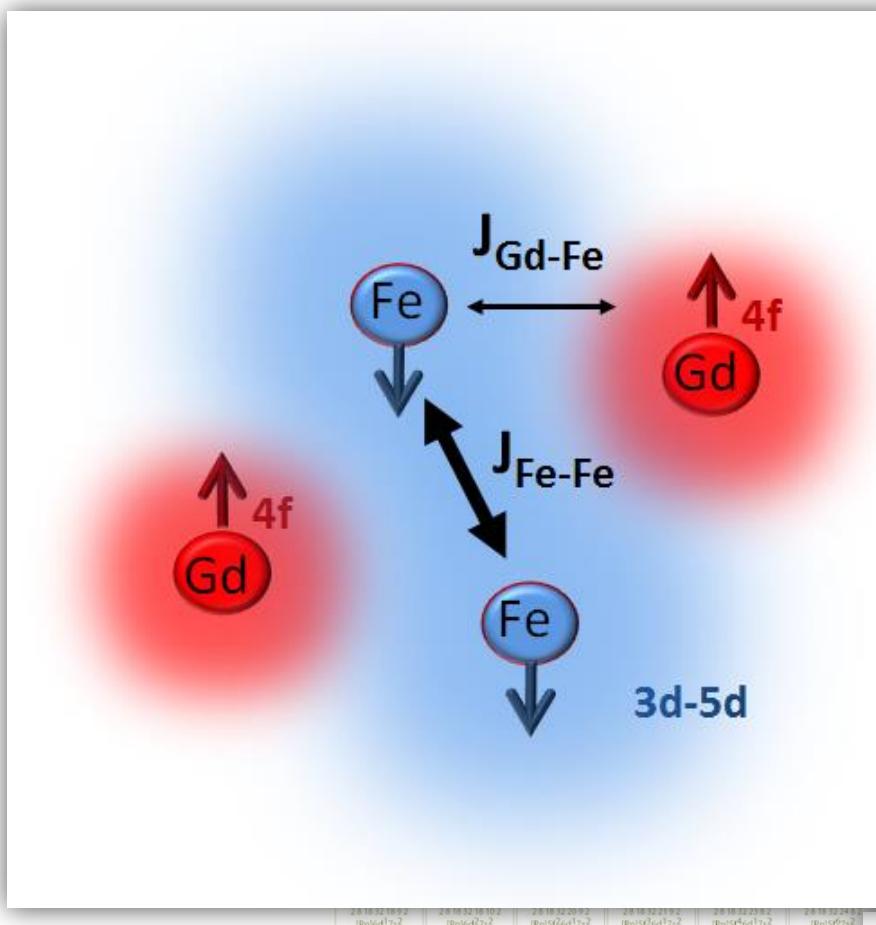
- Alkali Metal**: Red
- Alkaline Earth**: Orange
- Transition Metal**: Yellow-Green
- Basic Metal**: Green
- Metalloid**: Cyan
- Nonmetal**: Blue
- Halogens**: Purple
- Noble Gas**: Pink
- Lanthanide**: Light Green
- Actinide**: Light Blue

Rare earth-transition metals alloys

Periodic Table of the Elements																																																																																																							
18 VIIIA 8A																																																																																																							
1 IA 1A	2 IIA 2A	3 Li Lithium 3 [He]2s ¹	4 Be Beryllium 4 [He]2s ²	5 B Boron 5 [He]2s ² 2p ¹	6 C Carbon 6 [He]2s ² 2p ²	7 N Nitrogen 7 [He]2s ² 2p ³	8 O Oxygen 8 [He]2s ² 2p ⁴	9 F Fluorine 9 [He]2s ² 2p ⁵	10 Ne Neon 10 [He]2s ² 2p ⁶	11 Na Sodium 3 [Ne]3s ¹	12 Mg Magnesium 3 [Ne]3s ²	13 Al Aluminum 13 [Ne]3s ² 3p ¹	14 Si Silicon 14 [Ne]3s ² 3p ²	15 P Phosphorus 15 [Ne]3s ² 3p ³	16 S Sulfur 16 [Ne]3s ² 3p ⁴	17 Cl Chlorine 17 [Ne]3s ² 3p ⁵	18 Ar Argon 18 [Ne]3s ² 3p ⁶	19 K Potassium 19 [Ar]4s ¹	20 Ca Calcium 20 [Ar]4s ²	21 Sc Scandium 21 [Ar]3d ¹ 4s ²	22 Ti Titanium 22 [Ar]3d ² 4s ²	23 V Vanadium 23 [Ar]3d ³ 4s ²	24 Cr Chromium 24 [Ar]3d ⁵ 4s ¹	25 Mn Manganese 25 [Ar]3d ⁵ 4s ²	26 Fe Iron 26 [Ar]3d ⁶ 4s ²	27 Co Cobalt 27 [Ar]3d ⁷ 4s ²	28 Ni Nickel 28 [Ar]3d ⁸ 4s ²	29 Cu Copper 29 [Ar]3d ¹⁰ 4s ¹	30 Zn Zinc 30 [Ar]3d ¹⁰ 4s ²	31 Ga Gallium 31 [Ar]3d ¹⁰ 4s ² 4p ¹	32 Ge Germanium 32 [Ar]3d ¹⁰ 4s ² 4p ²	33 As Arsenic 33 [Ar]3d ¹⁰ 4s ² 4p ³	34 Se Selenium 34 [Ar]3d ¹⁰ 4s ² 4p ⁴	35 Br Bromine 35 [Ar]3d ¹⁰ 4s ² 4p ⁵	36 Kr Krypton 36 [Ar]3d ¹⁰ 4s ² 4p ⁶	37 Rb Rubidium 37 [Ar]4s ¹	38 Sr Strontium 38 [Ar]4s ²	39 Y Yttrium 39 [Ar]4s ² 4f ¹	40 Zr Zirconium 40 [Ar]4s ² 4f ²	41 Nb Niobium 41 [Ar]4s ² 4f ³	42 Mo Molybdenum 42 [Ar]4s ² 4f ⁵	43 Tc Technetium 43 [Ar]4s ² 4f ⁶	44 Ru Ruthenium 44 [Ar]4s ² 4f ⁷	45 Rh Rhodium 45 [Ar]4s ² 4f ⁸	46 Pd Palladium 46 [Ar]4s ² 4f ⁹	47 Ag Silver 47 [Ar]4s ² 4f ¹⁰	48 Cd Cadmium 48 [Ar]4s ² 4f ¹²	49 In Indium 49 [Ar]4s ² 4f ¹³	50 Sn Tin 50 [Ar]4s ² 4f ¹⁴	51 Sb Antimony 51 [Ar]4s ² 4f ¹⁵	52 Te Tellurium 52 [Ar]4s ² 4f ¹⁶	53 I Iodine 53 [Ar]4s ² 4f ¹⁷	54 Xe Xenon 54 [Ar]4s ² 4f ¹⁸	55 Cs Cesium 55 [Ar]4s ² 4f ¹⁹	56 Ba Barium 56 [Ar]4s ² 4f ²⁰	57-71 Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn Fr	72 Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn Fr	73 Ta Tantalum 73 [Ar]5s ² 4d ³ 5p ²	74 W Tungsten 74 [Ar]5s ² 4d ⁵ 5p ²	75 Re Rhenium 75 [Ar]5s ² 4d ⁷ 5p ²	76 Os Osmium 76 [Ar]5s ² 4d ⁹ 5p ²	77 Ir Iridium 77 [Ar]5s ² 4d ¹⁰ 5p ²	78 Pt Platinum 78 [Ar]5s ² 4d ¹¹ 5p ¹	79 Au Gold 79 [Ar]5s ² 4d ¹² 5p ¹	80 Hg Mercury 80 [Ar]5s ² 4d ¹³ 5p ¹	81 Tl Thallium 81 [Ar]5s ² 4d ¹⁴ 5p ¹	82 Pb Lead 82 [Ar]5s ² 4d ¹⁵ 5p ²	83 Bi Bismuth 83 [Ar]5s ² 4d ¹⁶ 5p ³	84 Po Polonium 84 [Ar]5s ² 4d ¹⁷ 5p ⁴	85 At Astatine 85 [Ar]5s ² 4d ¹⁸ 5p ⁵	86 Rn Radon 86 [Ar]5s ² 4d ¹⁹ 5p ⁶	87 Fr Francium 87 [Ar]5s ² 4d ²⁰ 5p ¹	88-103 Ra Rf Db Sg Bh Hs Mt Ds Rg Cn Uut Fl Uup Lv Uus Uuo	104 (281) Rf Rutherfordium 2.8 18 32 10 2 [Rn]5f ¹⁴ 6d ⁷ 7s ²	105 (262) Db Dubnium 2.8 18 32 12 11 [Rn]5f ¹⁴ 6d ⁷ 7s ²	106 (266) Sg Seaborgium 2.8 18 32 12 12 [Rn]5f ¹⁴ 6d ⁷ 7s ²	107 (264) Bh Bohrium 2.8 18 32 12 12 [Rn]5f ¹⁴ 6d ⁷ 7s ²	108 (269) Hs Hassium 2.8 18 32 12 12 [Rn]5f ¹⁴ 6d ⁷ 7s ²	109 (268) Mt Meitnerium 2.8 18 32 12 12 [Rn]5f ¹⁴ 6d ⁷ 7s ²	110 (269) Ds Darmstadtium 2.8 18 32 12 12 [Rn]5f ¹⁴ 6d ⁷ 7s ²	111 (272) Rg Roentgenium 2.8 18 32 12 12 [Rn]5f ¹⁴ 6d ⁷ 7s ²	112 (277) Cn Copernicium 2.8 18 32 12 12 [Rn]5f ¹⁴ 6d ⁷ 7s ²	113 unknown Unknown 114 Fl Flerovium 114 [Rn]5f ¹⁴ 6d ⁷ 7s ²	115 unknown Unknown 116 Lv Livermorium 116 [Rn]5f ¹⁴ 6d ⁷ 7s ²	117 unknown Unknown 118 Uuo Ununoctetium 118 [Rn]5f ¹⁴ 6d ⁷ 7s ²	57 La Lanthanum 2.8 18 19 2 [Xe]5d ¹ 6s ²	58 Ce Cerium 2.8 18 20 2 [Xe]4f ¹ 5d ¹ 6s ²	59 Pr Praseodymium 2.8 18 22 2 [Xe]4f ² 5d ¹ 6s ²	60 Nd Neodymium 2.8 18 22 2 [Xe]4f ³ 5d ¹ 6s ²	61 Pm Promethium 2.8 18 22 2 [Xe]4f ⁵ 5d ¹ 6s ²	62 Sm Samarium 2.8 18 24 2 [Xe]4f ⁶ 5d ¹ 6s ²	63 Eu Europium 2.8 18 24 2 [Xe]4f ⁷ 5d ¹ 6s ²	64 Gd Gadolinium 2.8 18 25 2 [Xe]4f ⁹ 5d ¹ 6s ²	65 Tb Terbium 2.8 18 27 2 [Xe]4f ¹⁰ 5d ¹ 6s ²	66 Dy Dysprosium 2.8 18 28 2 [Xe]4f ¹² 5d ¹ 6s ²	67 Ho Holmium 2.8 18 28 2 [Xe]4f ¹³ 5d ¹ 6s ²	68 Er Erbium 2.8 18 32 [Xe]4f ¹⁴ 6s ²	69 Tm Thulium 2.8 18 32 [Xe]4f ¹⁵ 6s ²	70 Yb Ytterbium 2.8 18 32 [Xe]4f ¹⁶ 6s ²	71 Lu Lutetium 2.8 18 32 [Xe]4f ¹⁷ 6s ²	1 H Hydrogen 1 [He]1s ¹	2 He Helium 2 [He]2s ²	1 IA 1A
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Rare earth-transition metals alloys

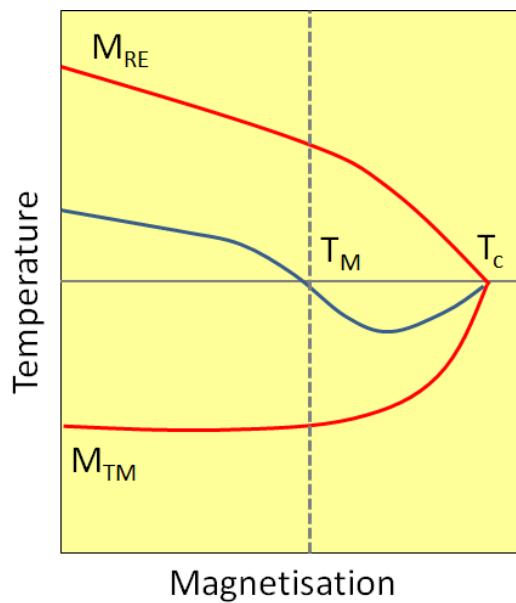


of the Elements

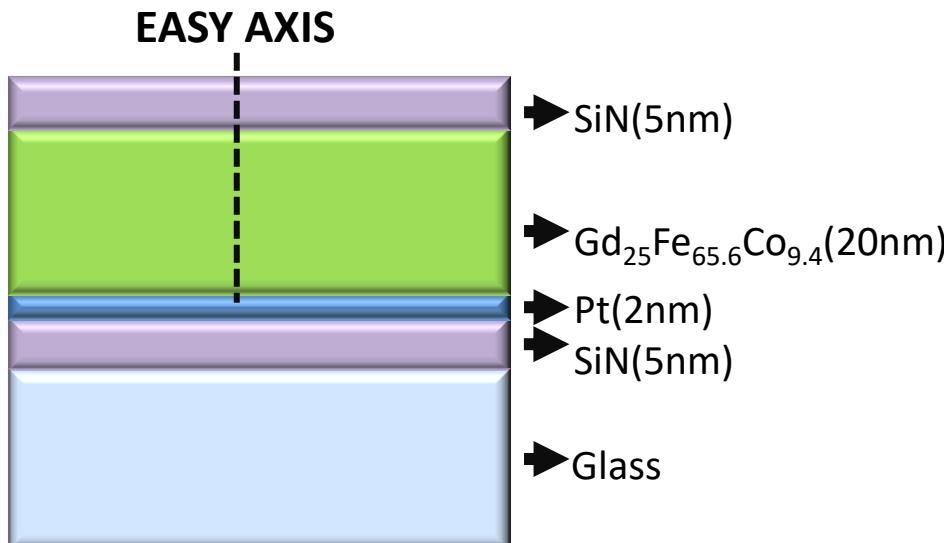
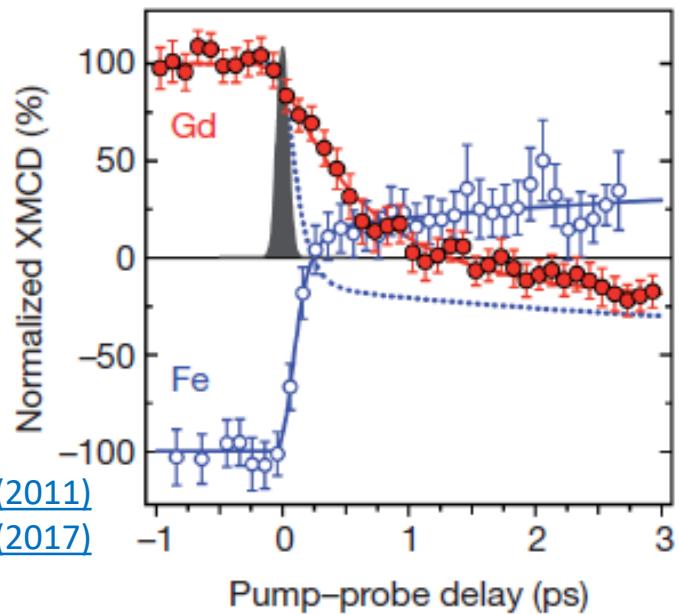
		18 VIIIA 8A	2 He Helium $1s^2$
Symbol	Name	Atomic Mass	10 Neon $1s^2 2s^2 2p^6$
13 B	Boron	10.811	11 IB 1B
14 C	Carbon	12.011	12 IIB 2B
15 N	Nitrogen	14.007	16 VIA 6A
16 O	Oxygen	15.999	17 VIIA 7A
17 F	Fluorine	18.998	18 Ar Argon
18 Ne	Neon	20.180	2 He Helium $1s^2$
5 Al	Aluminum	26.982	13 Al
13 Si	Silicon	28.086	14 P
15 S	Phosphorus	30.974	16 S
17 Cl	Sulfur	32.066	17 Cl
18 Ar	Chlorine	35.453	18 Ar
33 Ni	Nickel	58.693	28 Ni
29 Cu	Copper	63.546	30 Cu
30 Zn	Zinc	65.38	31 Zn
31 Ga	Gallium	69.723	32 Ge
32 Ge	Germanium	72.631	33 As
33 Se	Arsenic	74.922	34 Se
35 Br	Selenium	78.971	35 Br
36 Kr	Bromine	79.904	36 Kr
53 I	Iodine	84.798	54 Xe
54 Xe	Xenon	126.904	55 Rn
46 Pd	Palladium	106.42	47 Ag
47 Ag	Silver	107.868	48 Cd
48 Cd	Cadmium	112.414	49 In
49 In	Inium	114.818	50 Sn
50 Sn	Tin	118.711	51 Sb
51 Sb	Antimony	121.760	52 Te
52 Te	Tellurium	127.6	53 I
53 I	Iodine	126.904	54 Xe
78 Pt	Platinum	195.08	79 Au
79 Au	Gold	196.967	80 Hg
80 Hg	Mercury	200.592	81 Tl
81 Tl	Thallium	204.383	82 Pb
82 Pb	Lead	207.2	83 Bi
83 Bi	Bismuth	208.980	84 Po
84 Po	Polonium	208.987	85 At
85 At	Astatine	209.987	86 Rn
86 Rn	Radon	222.018	110 Ds
110 Ds	Darmstadtium	269.0	111 Rg
111 Rg	Roentgenium	272.0	112 Cn
112 Cn	Copernicium	277.0	113 Uut
113 Uut	Ununtrium	28.0	114 Fl
114 Fl	Flerovium	32.0	115 Uup
115 Uup	Ununpentium	32.0	116 Lv
116 Lv	Livermorium	32.0	117 Uus
117 Uus	Ununseptium	32.0	118 Uuo
118 Uuo	Ununoctium	32.0	151.964 Eu
151.964 Eu	Europium	152.592	152.061 Am
152.061 Am	Americium	152.592	157.25 Gd
157.25 Gd	Gadolinium	158.925	158.925 Tb
158.925 Tb	Terbium	162.500	162.500 Dy
162.500 Dy	Dysprosium	164.930	164.930 Ho
164.930 Ho	Holmium	167.259	167.259 Er
167.259 Er	Erbium	168.934	168.934 Tm
168.934 Tm	Thulium	170.105	170.105 Yb
170.105 Yb	Ytterbium	173.055	173.055 Lu
173.055 Lu	Lutetium	174.967	174.967 Met
174.967 Met	Metal		



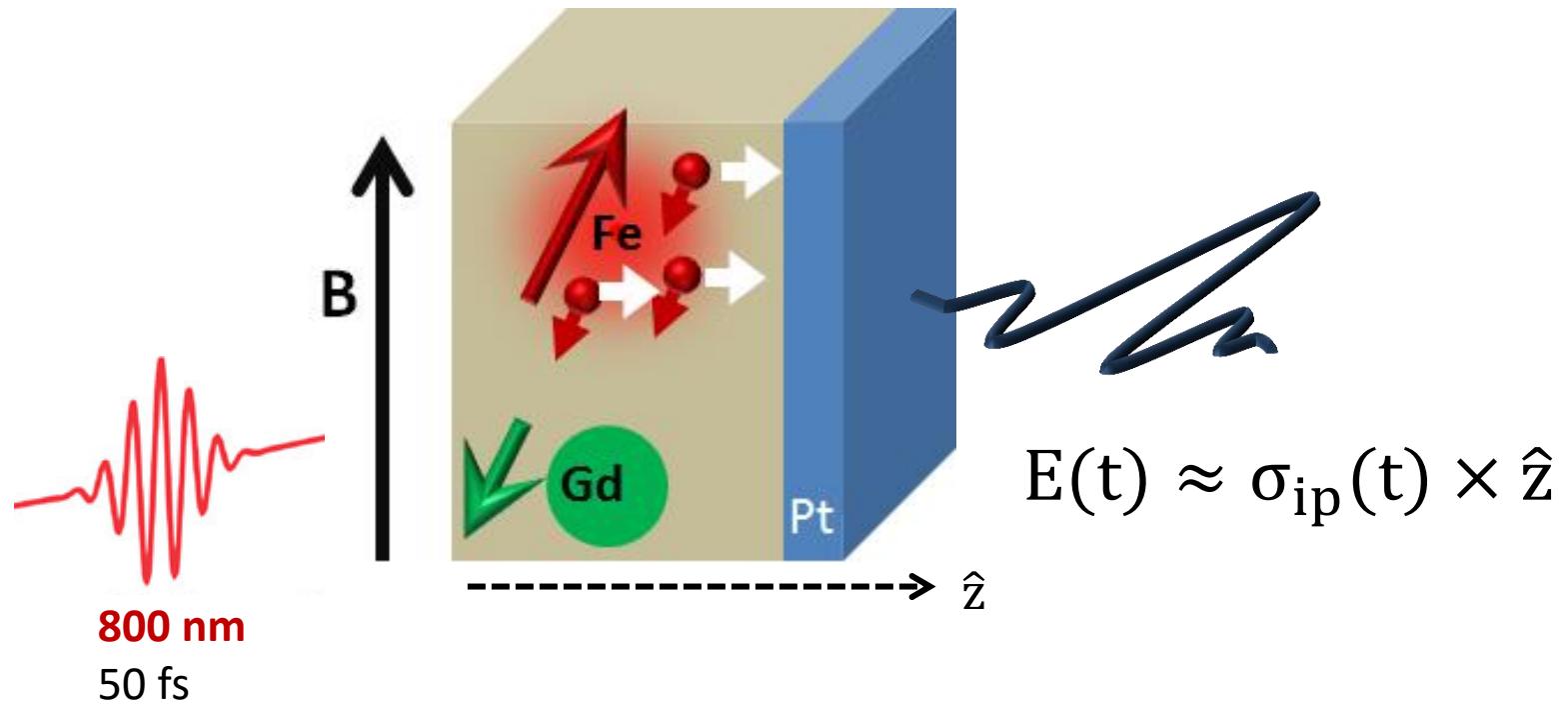
GdFeCo has a compensation temperature at which $M=0$



[Radu, Nature 472, 205 \(2011\)](#)
[Becker, PRL 118, 117203 \(2017\)](#)

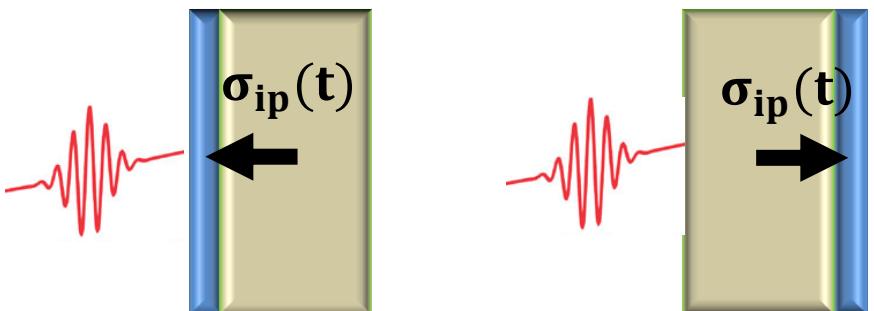
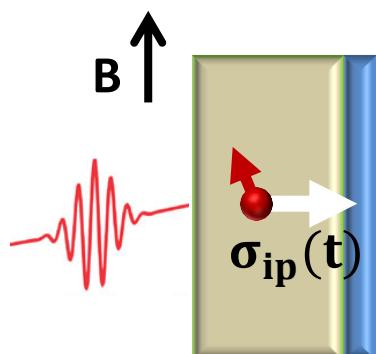
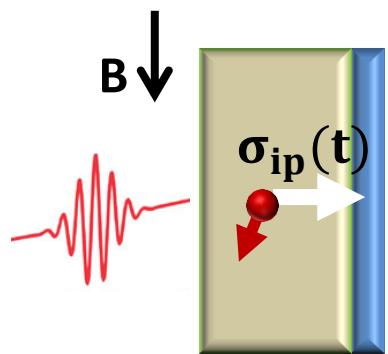
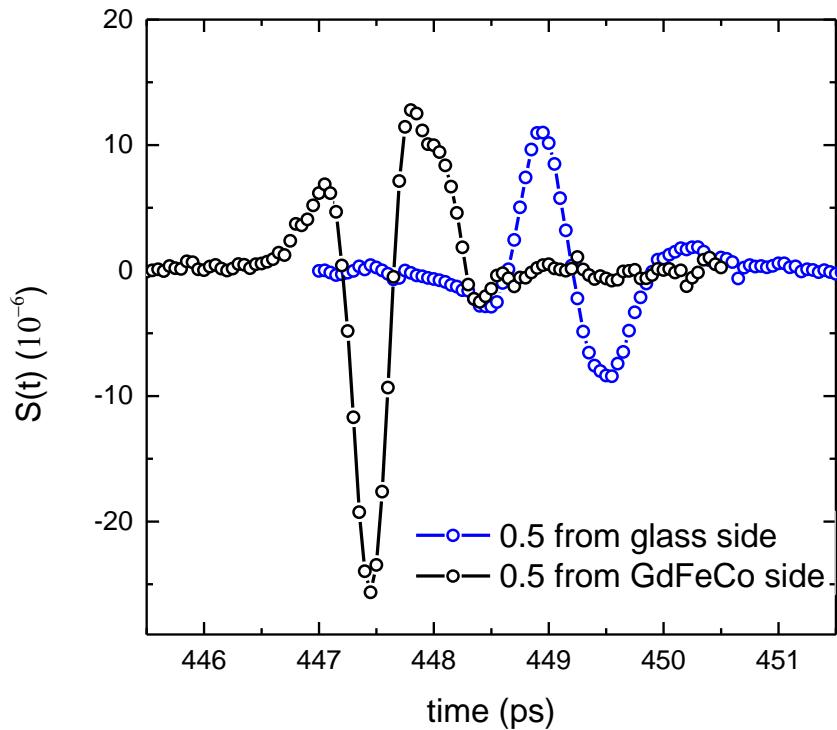
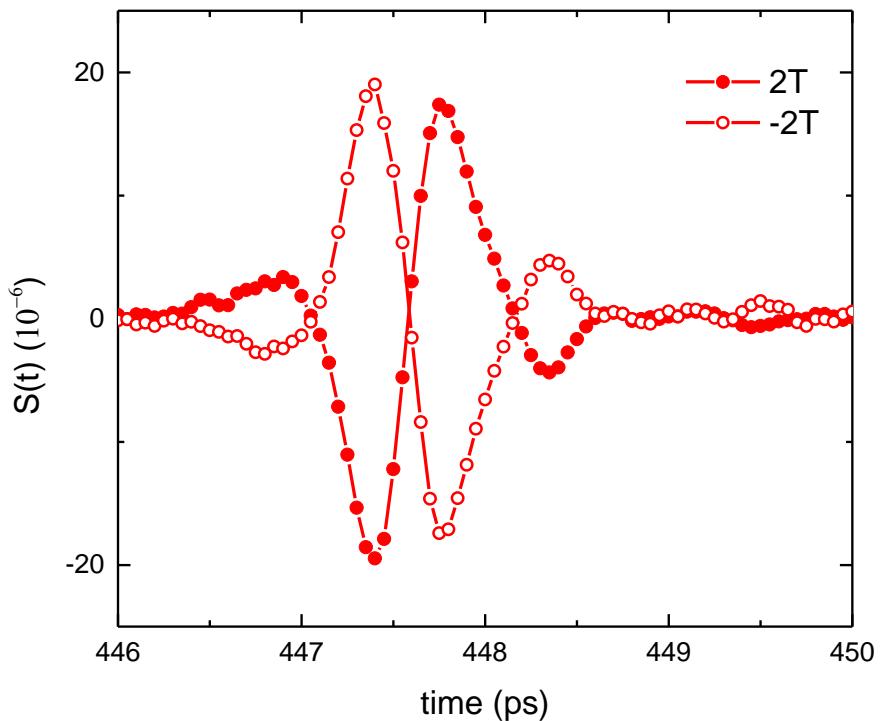


We use THz emission spectroscopy to measure spin-emission

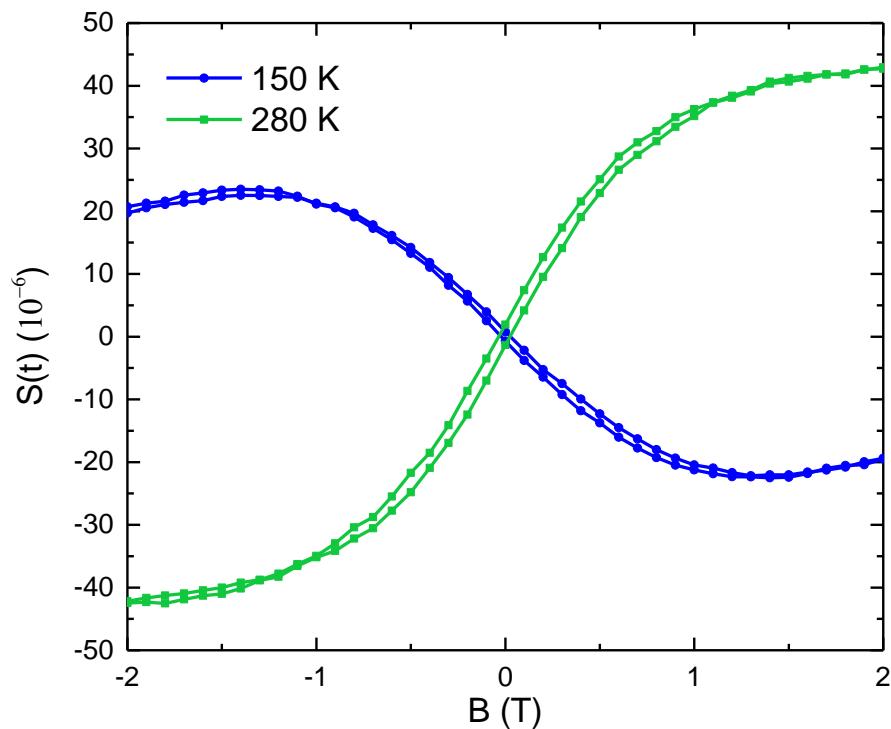


The emitted THz radiation has the symmetry of the ISHE

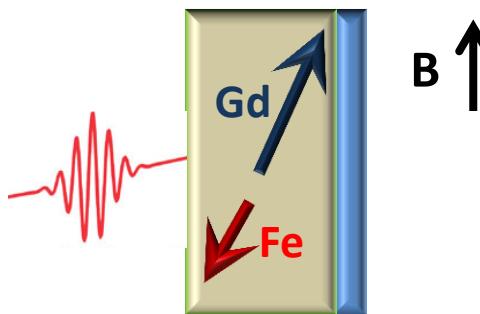
ROOM TEMPERATURE



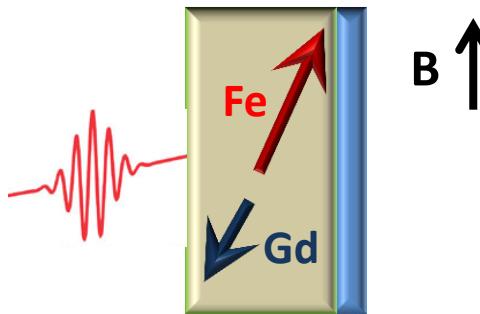
The emitted THz radiation is sensitive to the Fe spin only



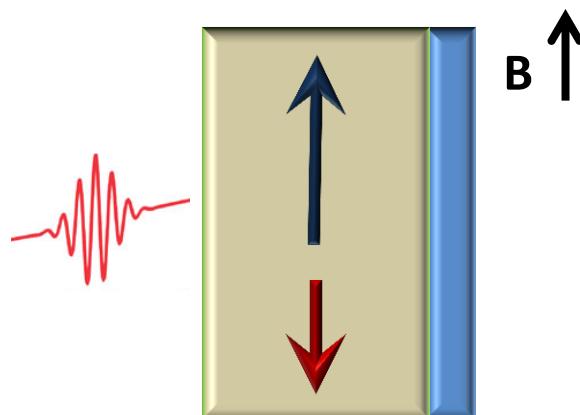
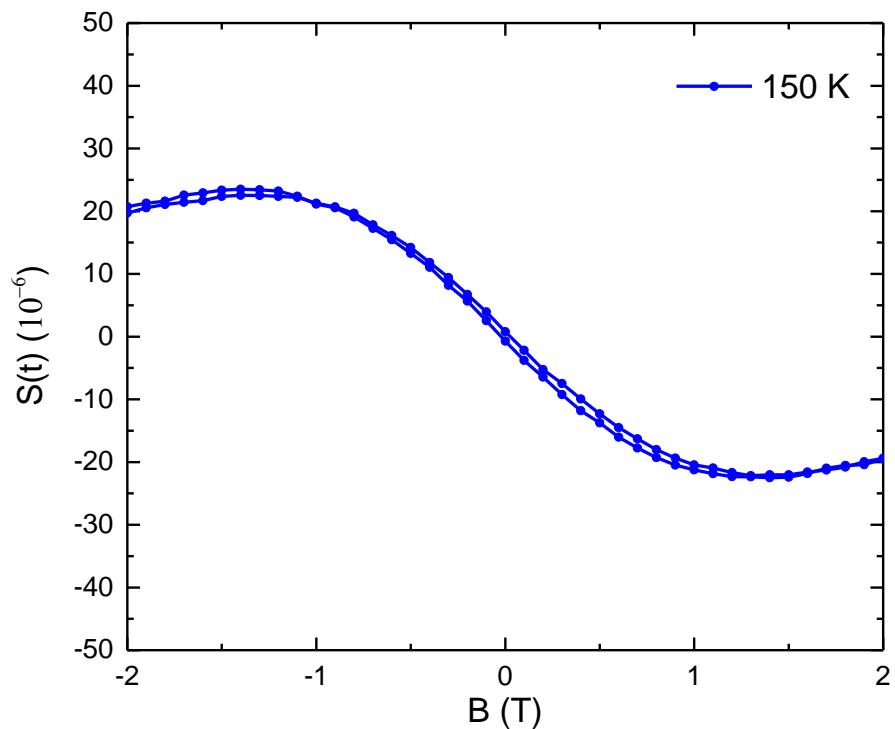
BELOW T_{comp}



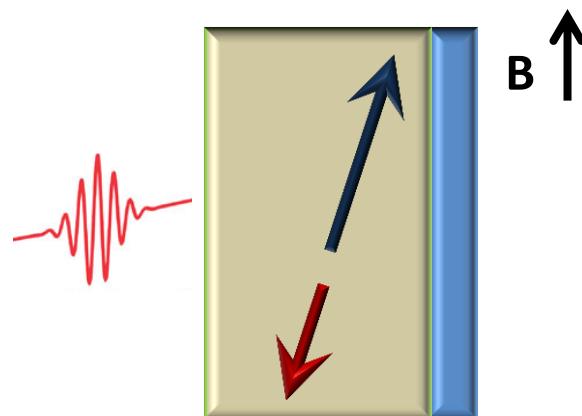
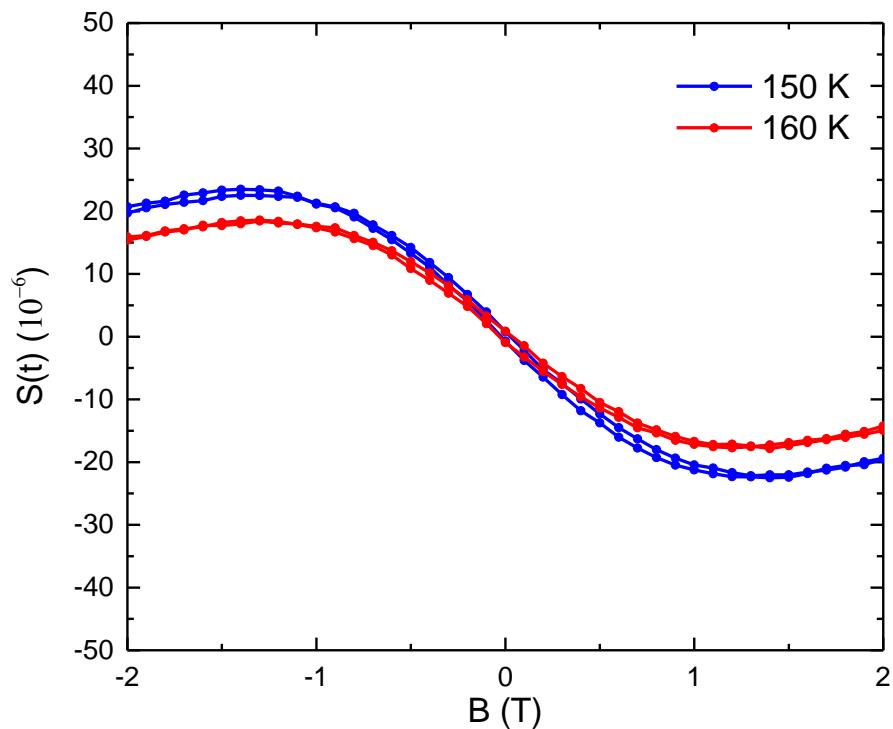
ABOVE T_{comp}



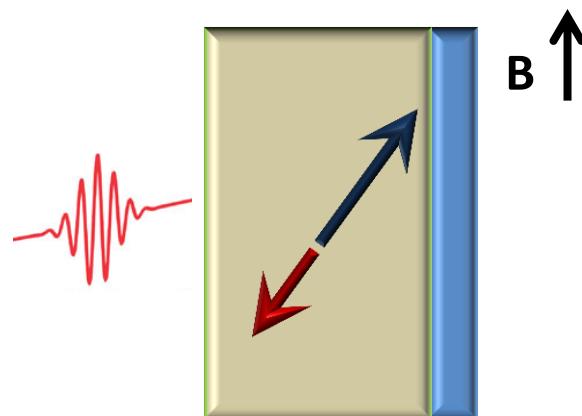
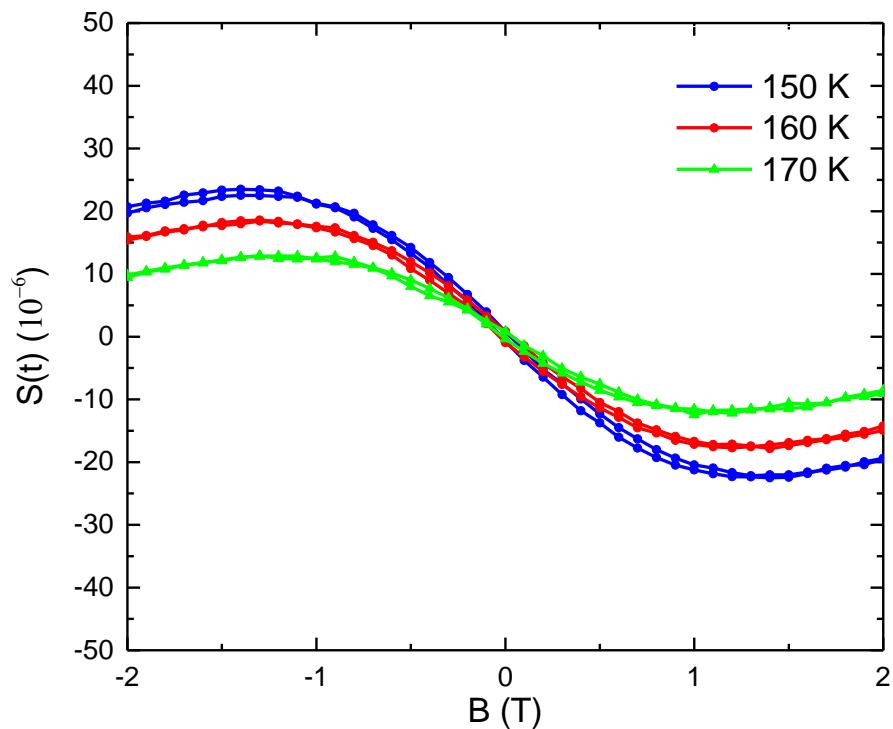
The emitted THz radiation is sensitive to the Fe spin only



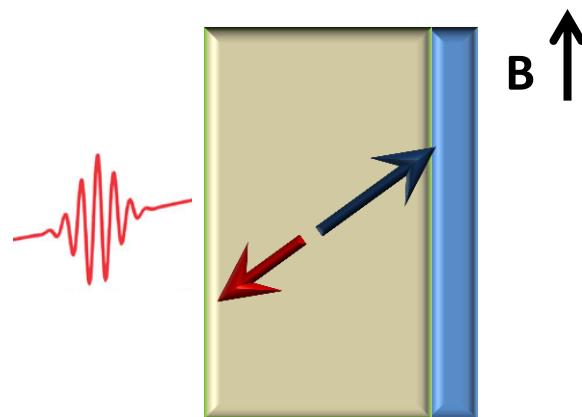
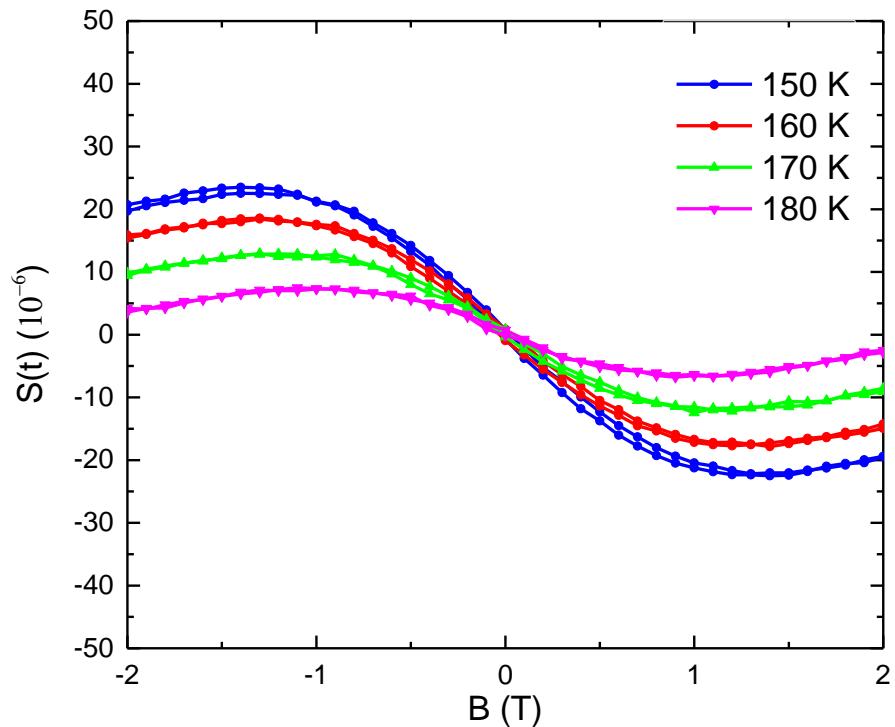
The emitted THz radiation is sensitive to the Fe spin only



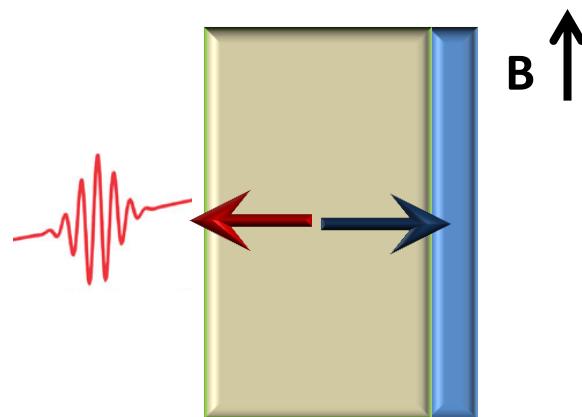
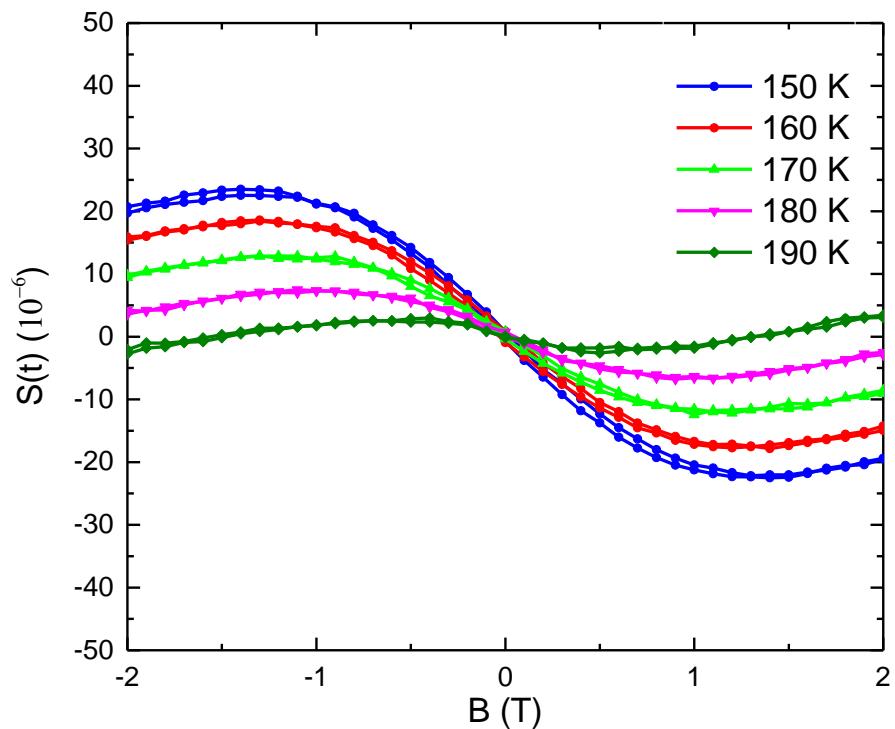
The emitted THz radiation is sensitive to the Fe spin only



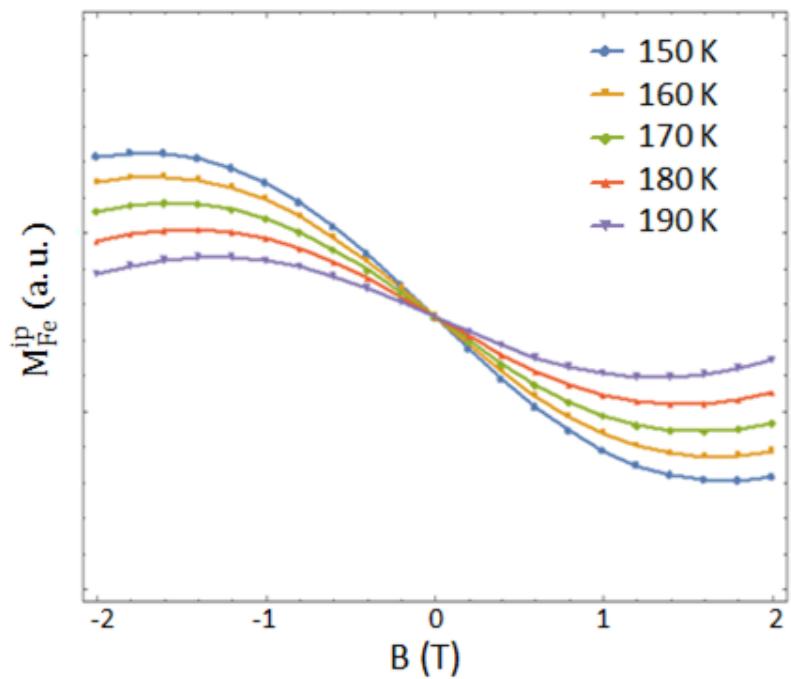
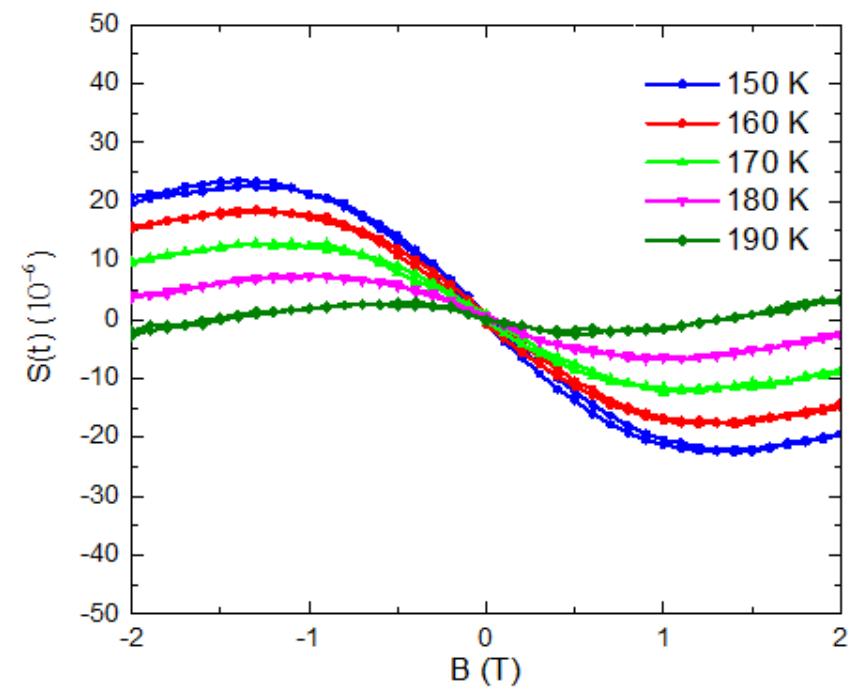
The emitted THz radiation is sensitive to the Fe spin only



The emitted THz radiation is sensitive to the Fe spin only



The emitted THz radiation is sensitive to the Fe spin only

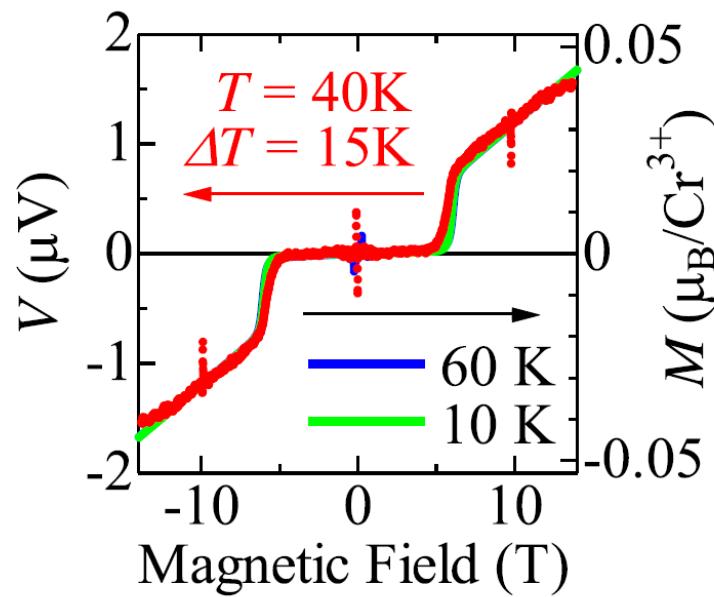
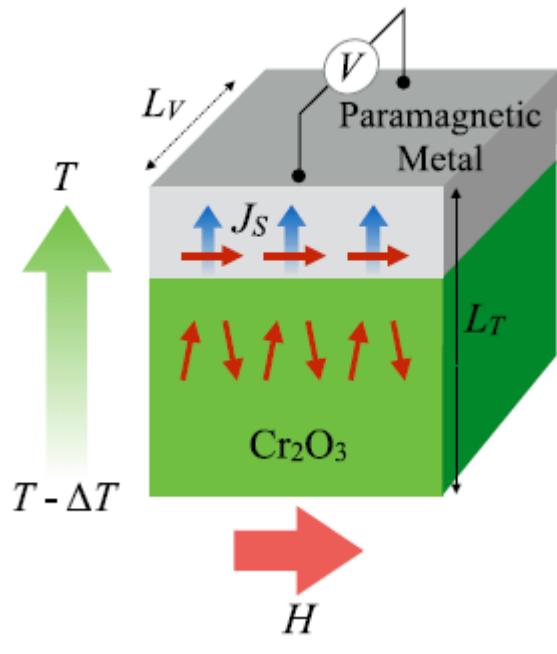


$$E = -M_1 B \sin(\theta_1) - M_2 B \sin(\theta_2) + JM_1 M_2 \cos(\theta_1 + \theta_2) - \frac{K}{2} M_1^2 \cos^2(\theta) - \frac{K}{2} M_2^2 \cos^2(\varphi)$$

EXPERIMENT 2

Spin-Seebeck effect in antiferromagnets

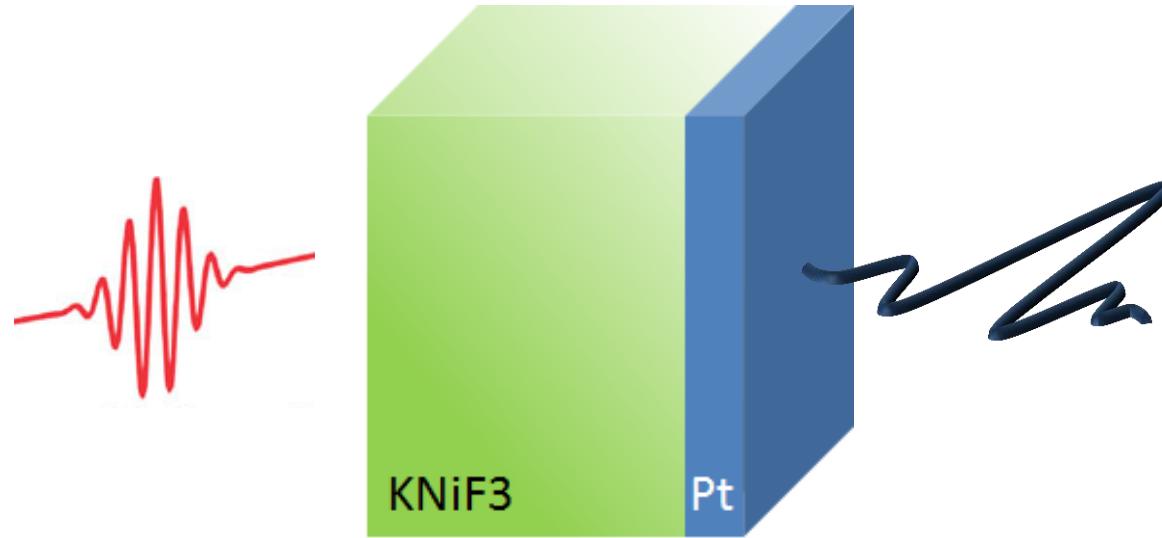
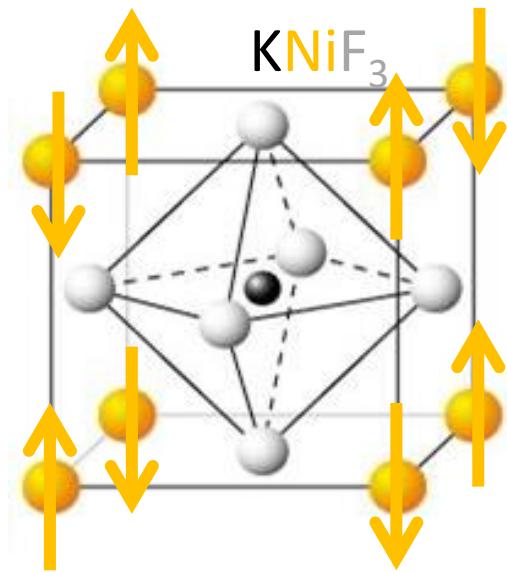
Spin-Seebeck in the DC limit



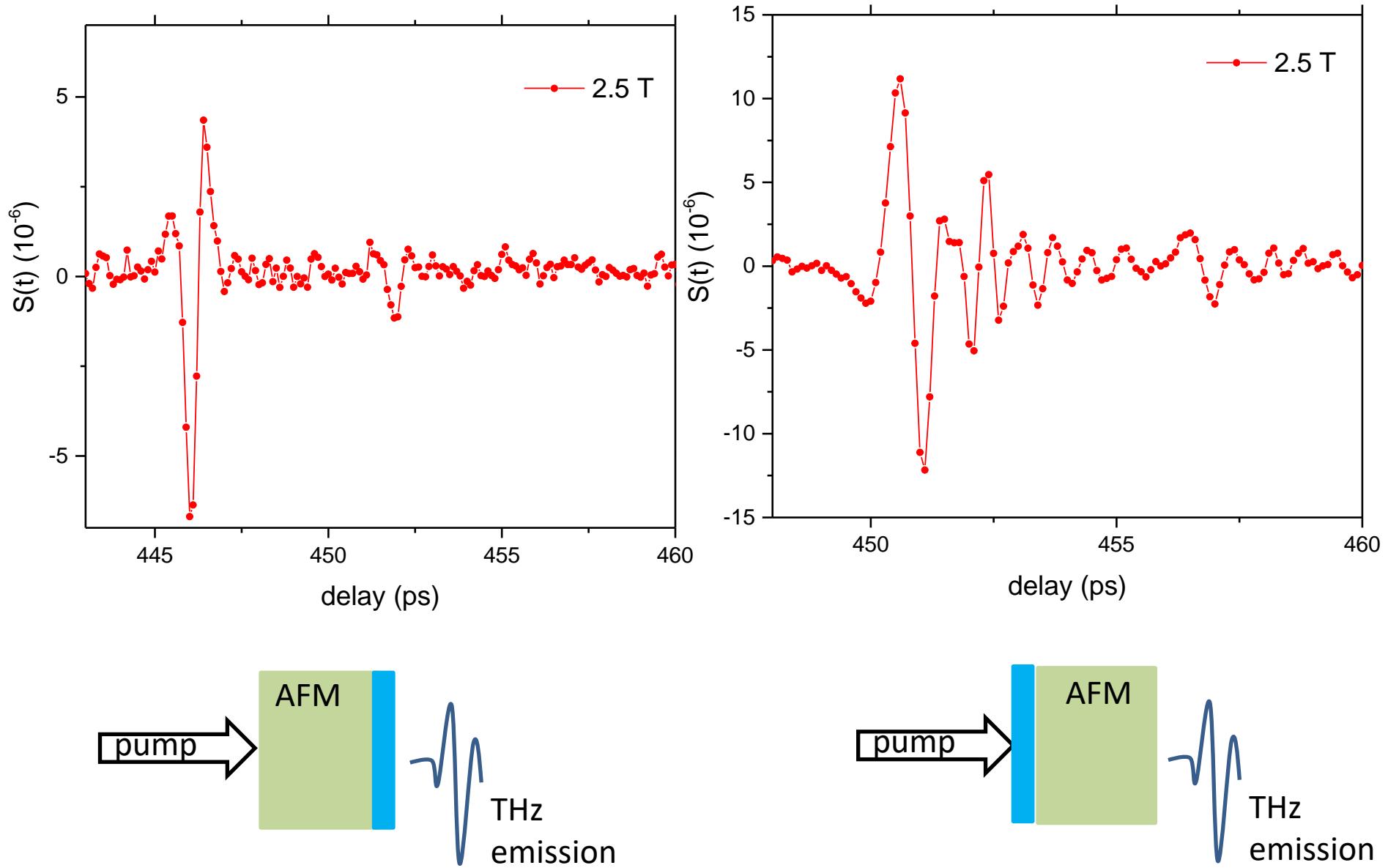
[S. Seki, PRL 115, 266601 \(2015\)](#)

[S.M. Wu et al., PRL 116, 097204 \(2016\)](#)

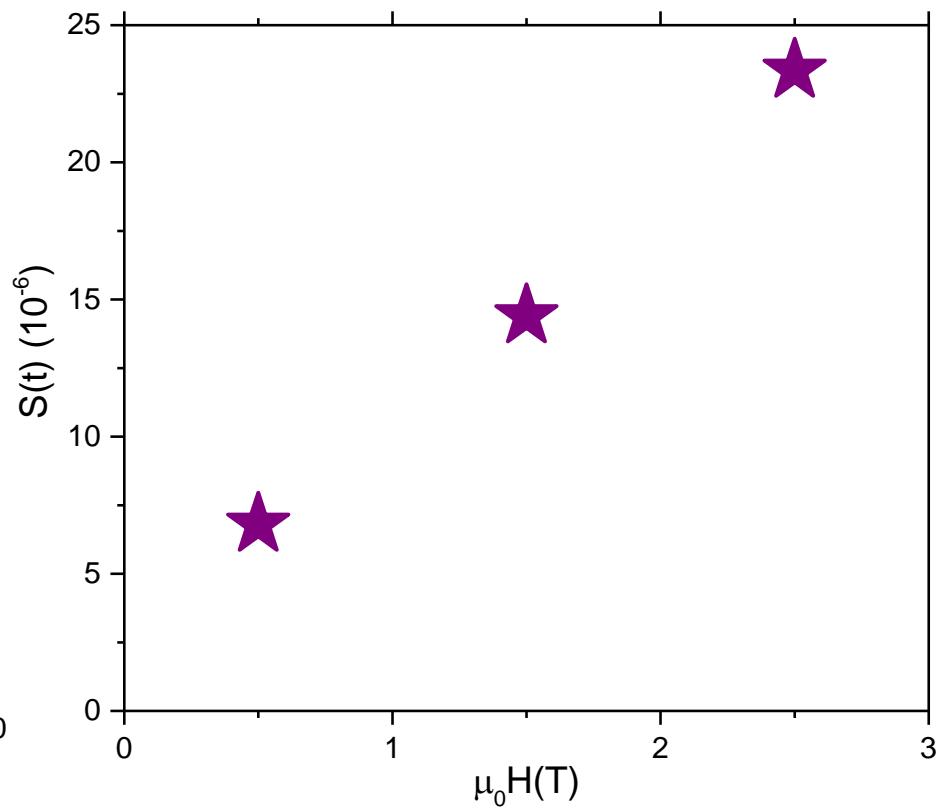
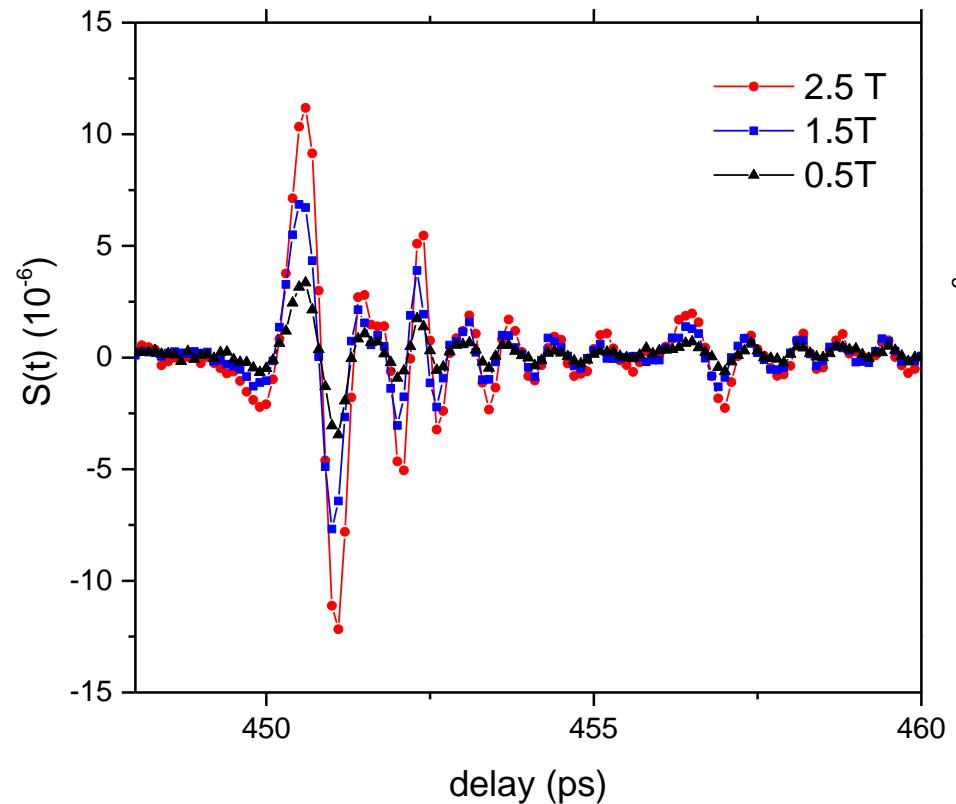
Spin-Seebeck in the picosecond limit



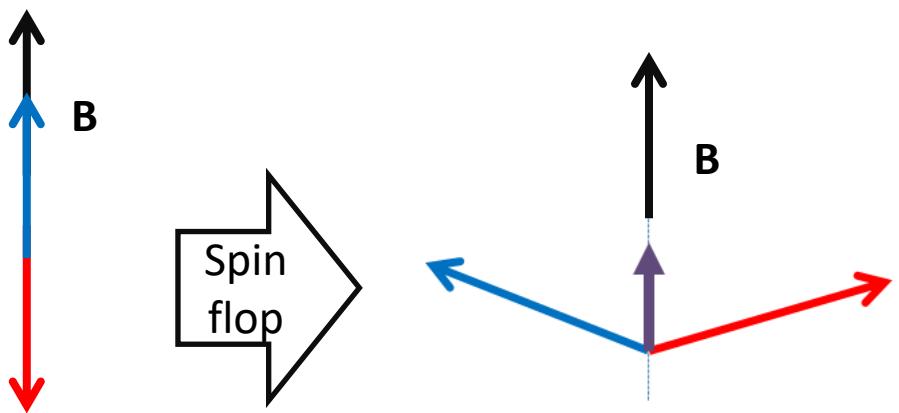
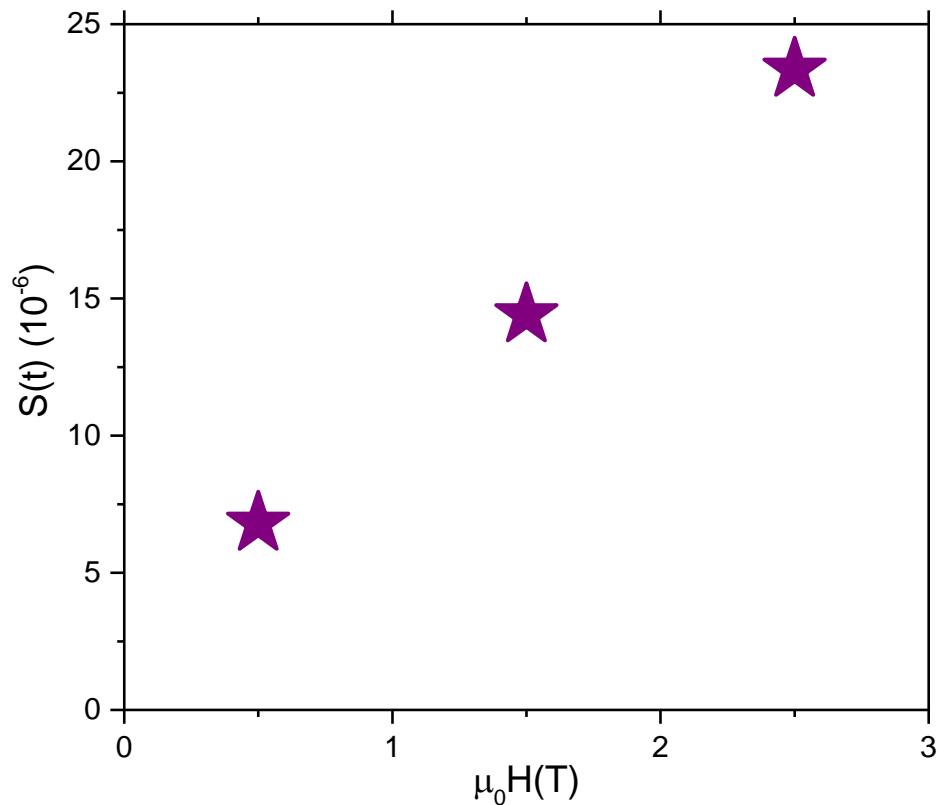
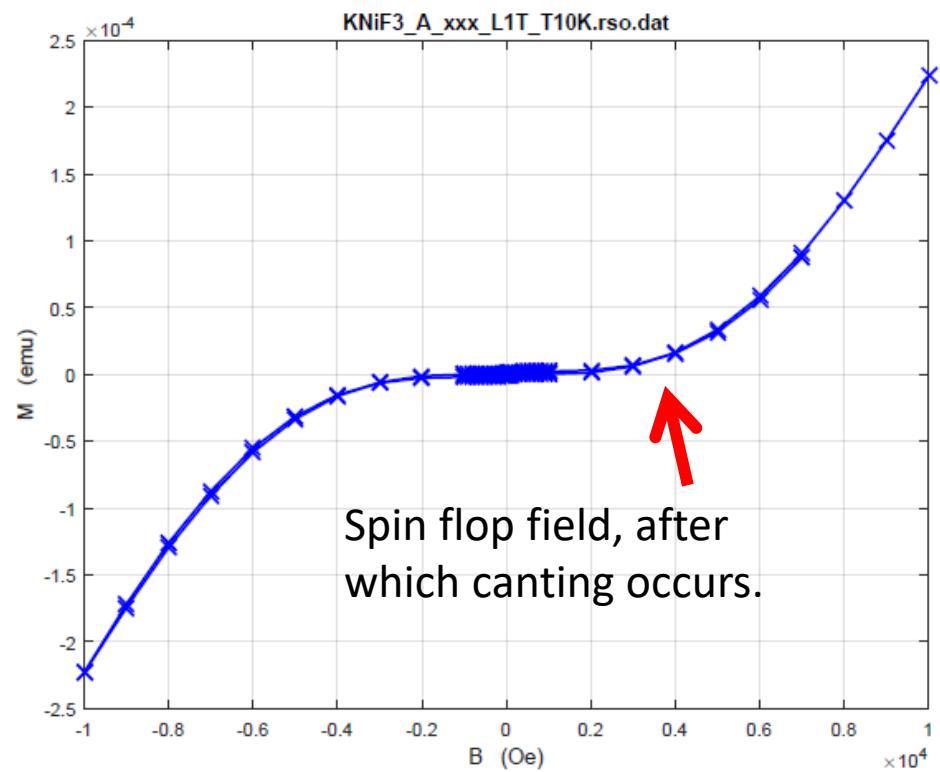
A broad-band THz radiation is emitted from the Pt



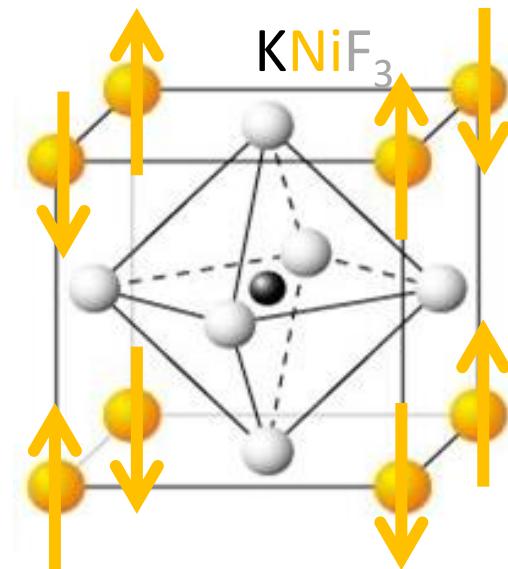
The THz emission is linear in magnetic field



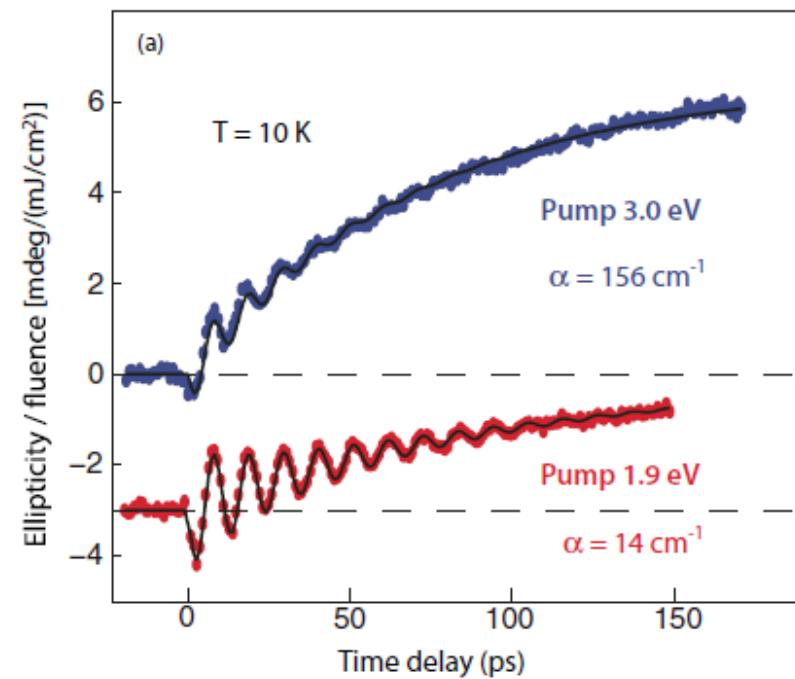
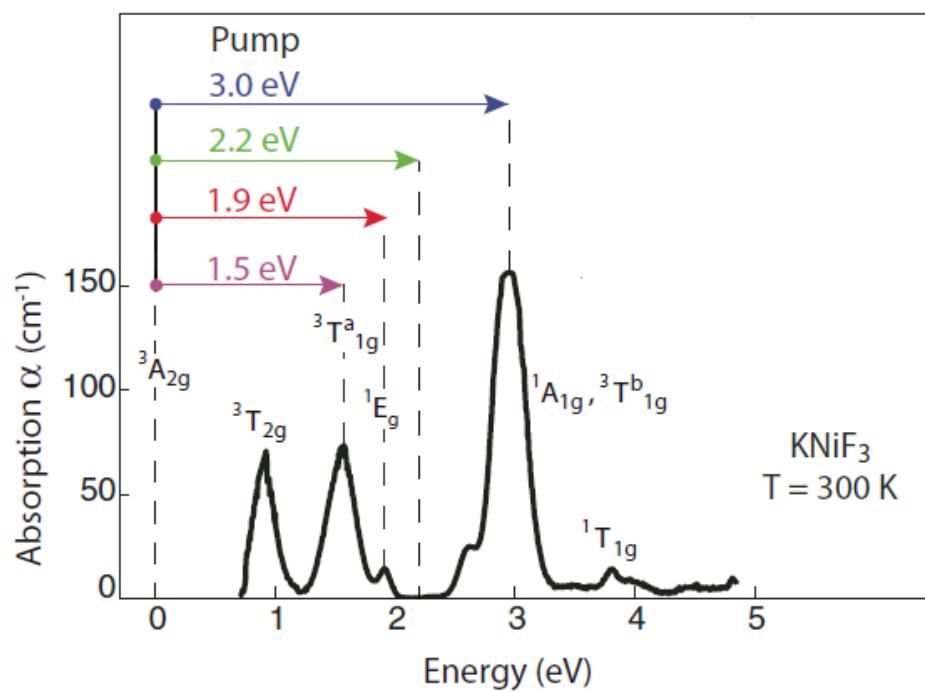
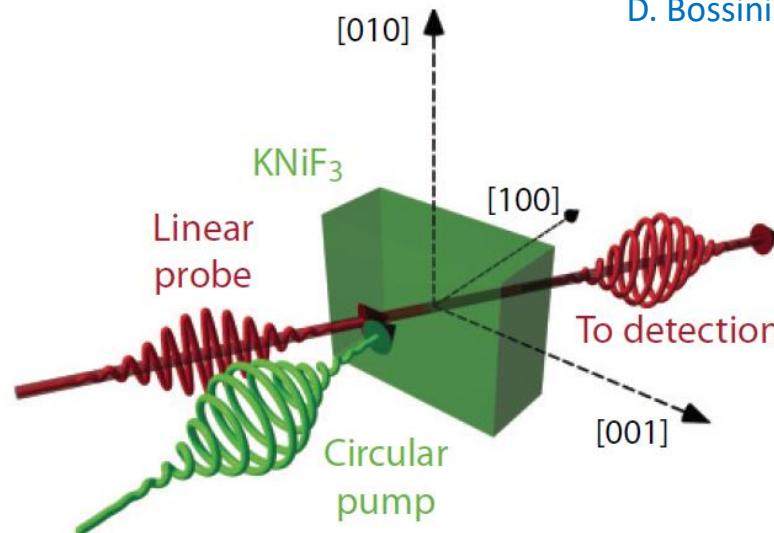
The THz emission is linear in magnetic field

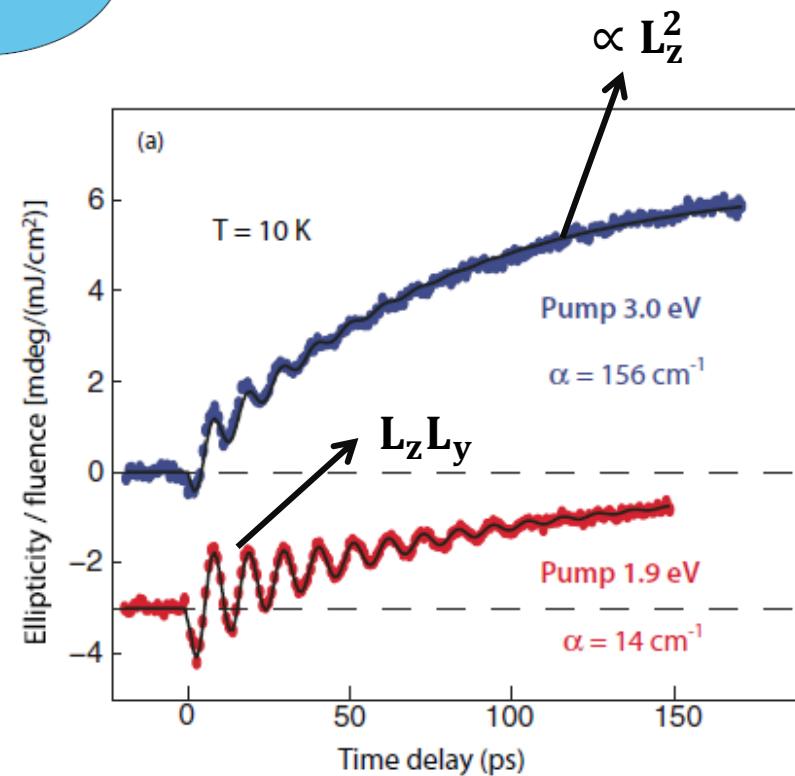
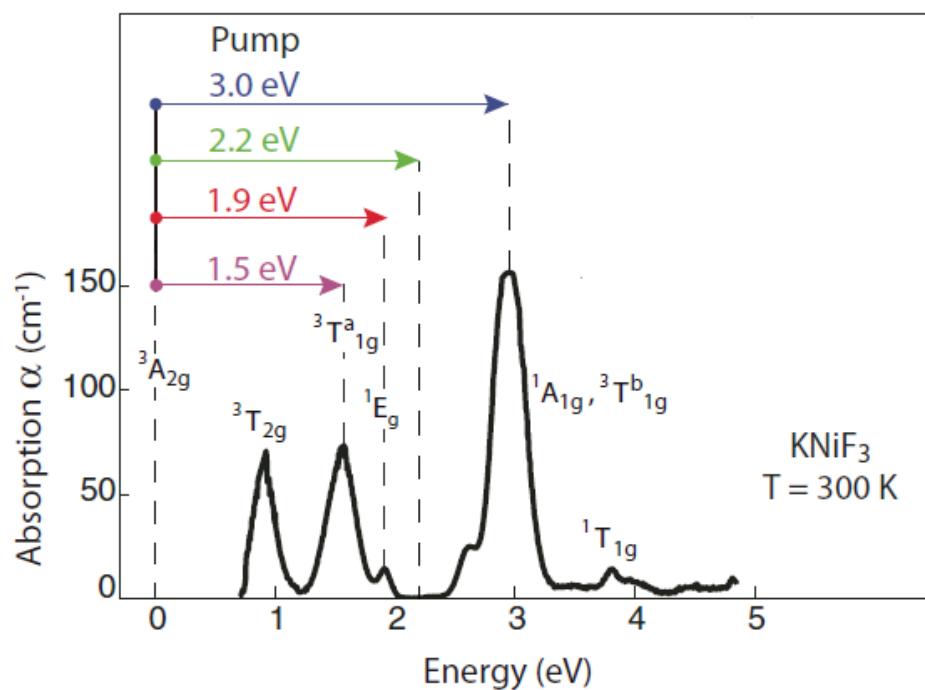
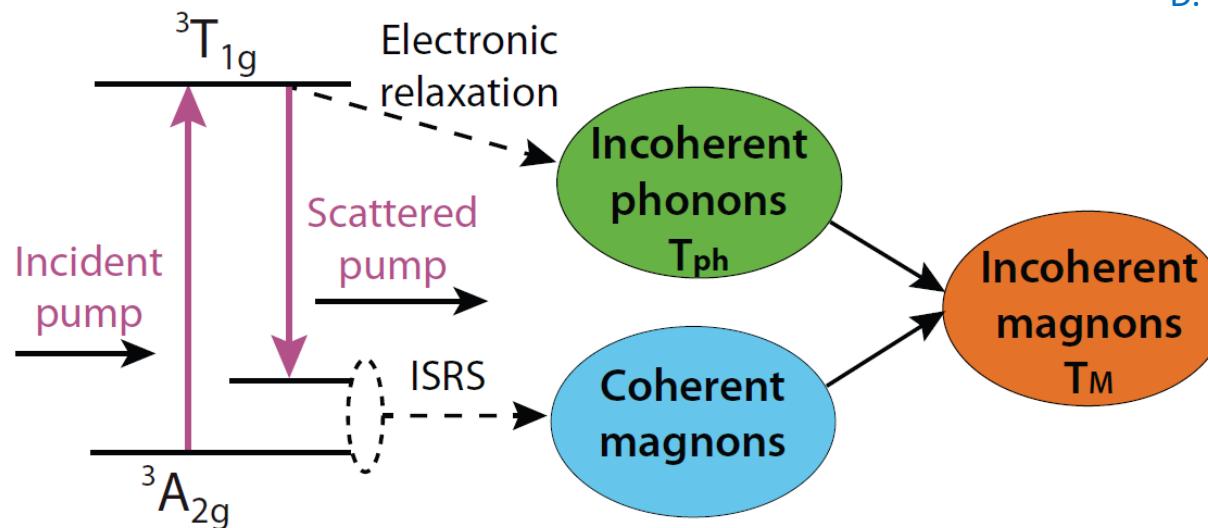


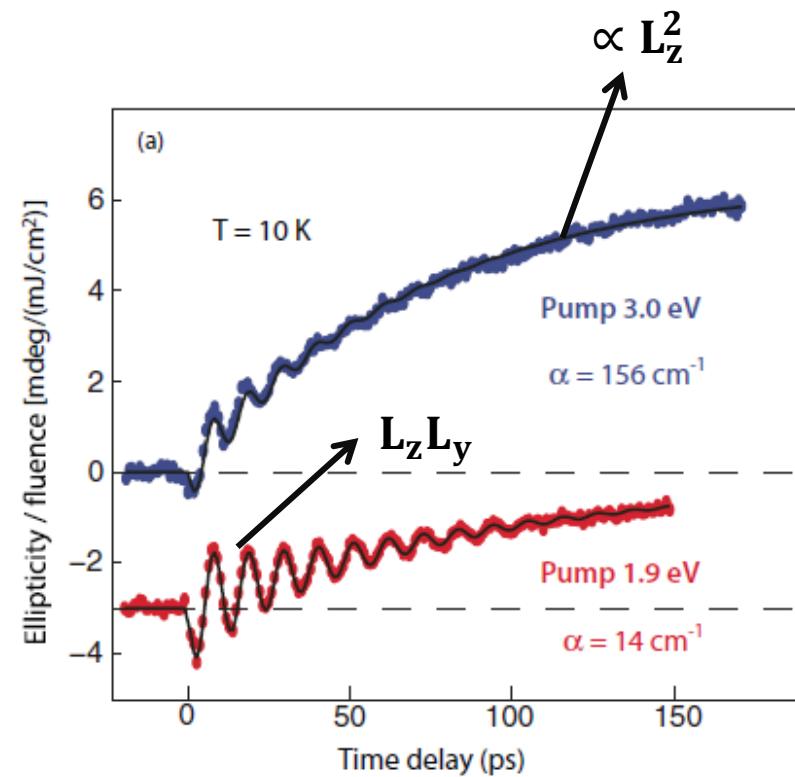
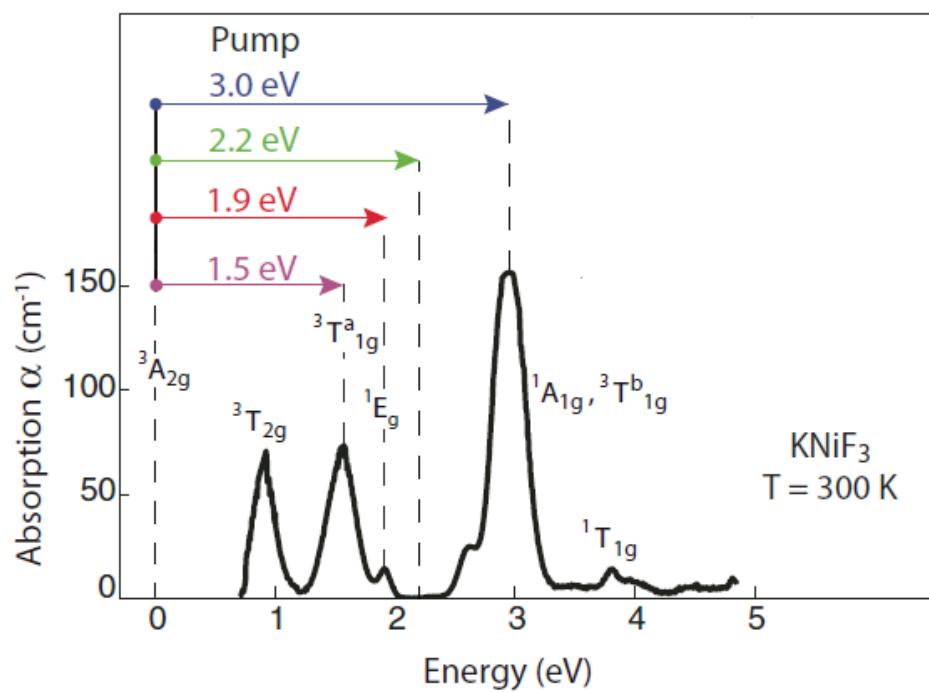
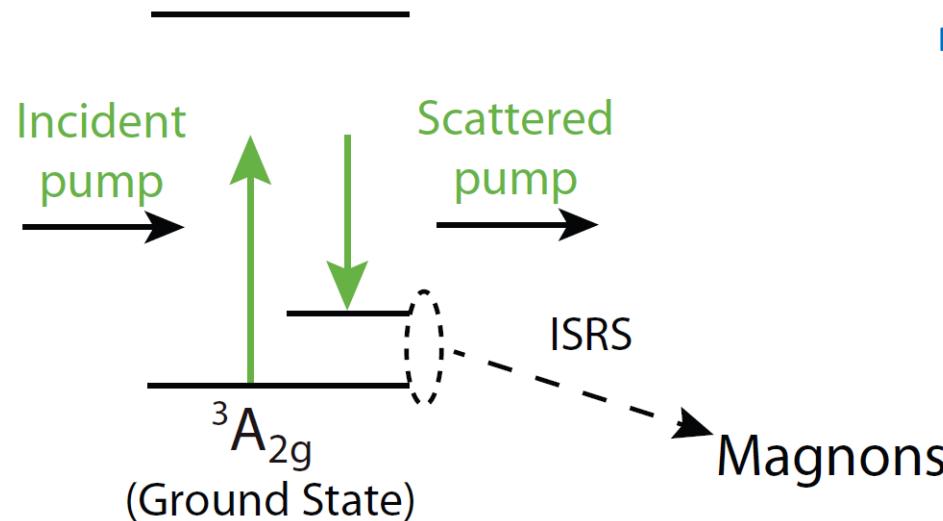
KNiF_3



D. Bossini et al., PRB 2014

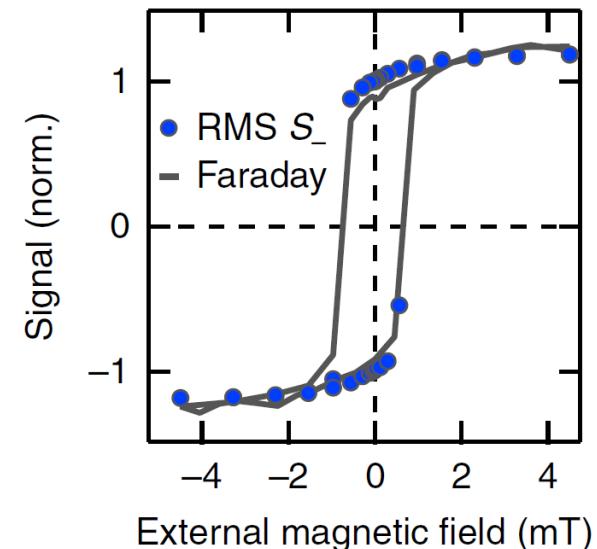
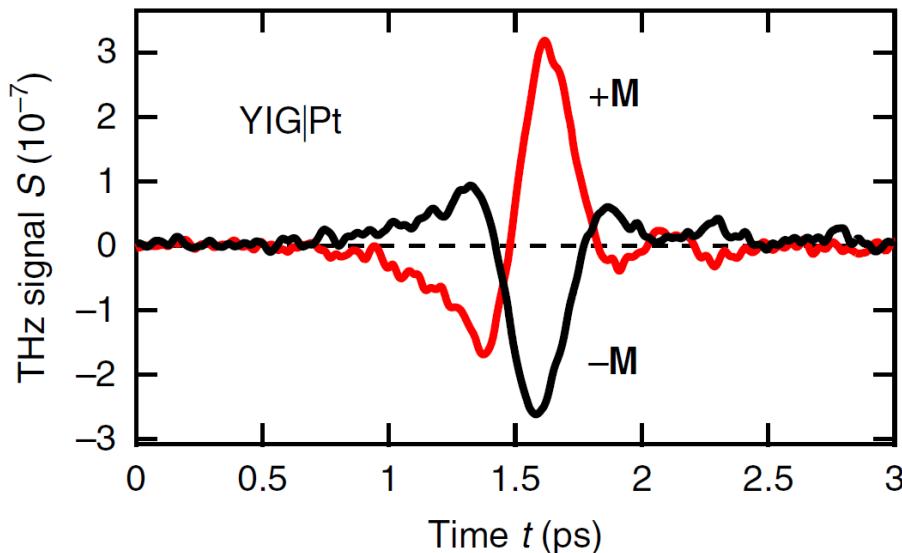
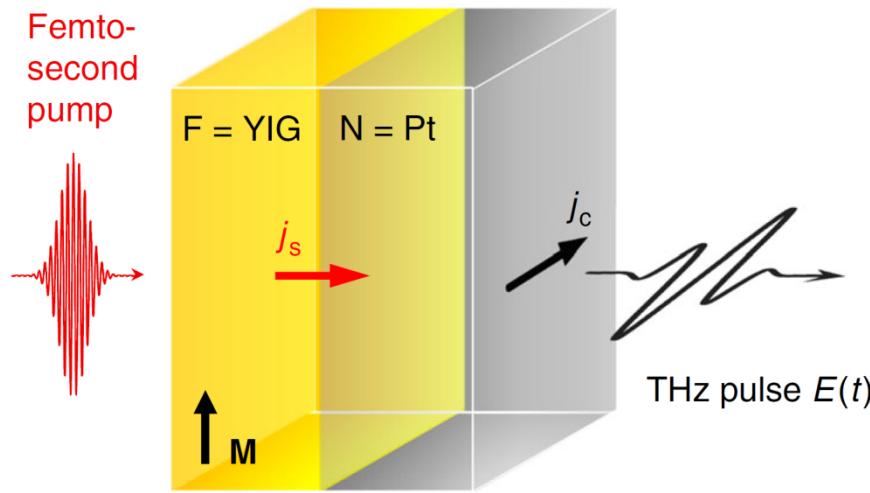




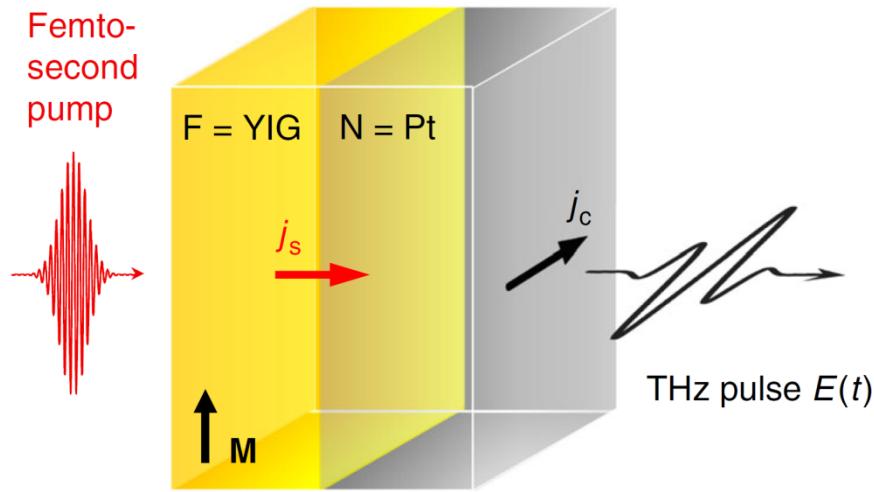


Ultra-fast spin-Seebeck in YIG/Pt

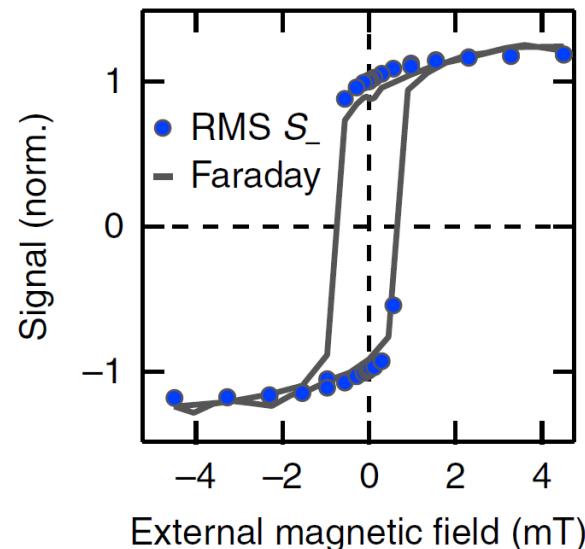
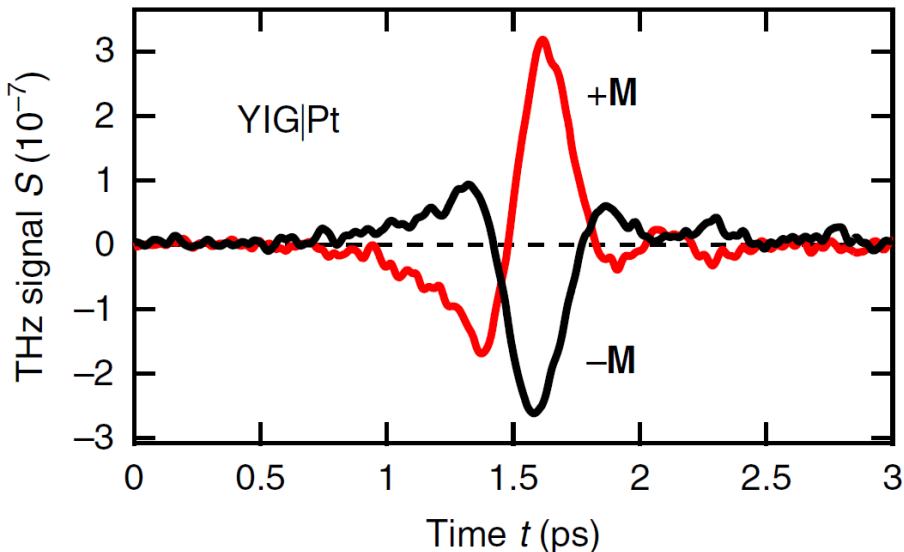
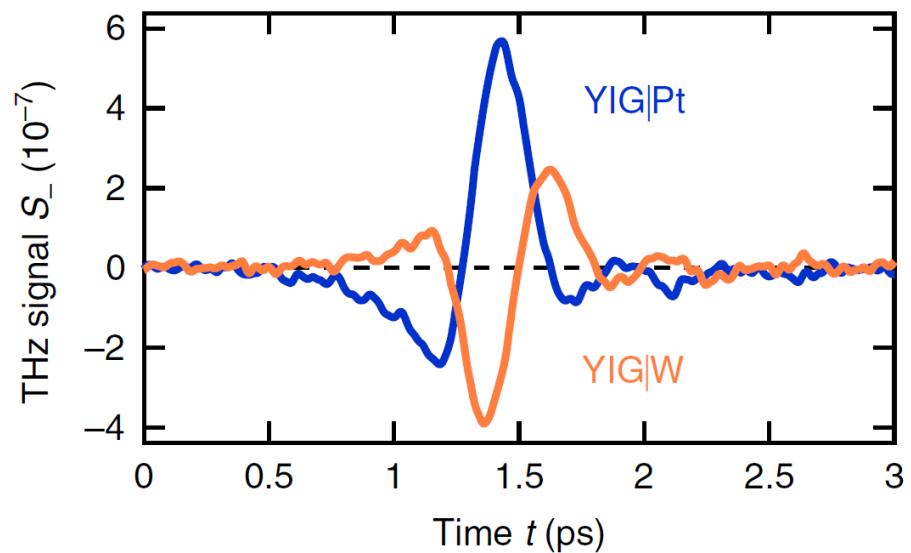
Seifert et al., Nature Comm. 2018



Ultra-fast spin-Seebeck in YIG/Pt

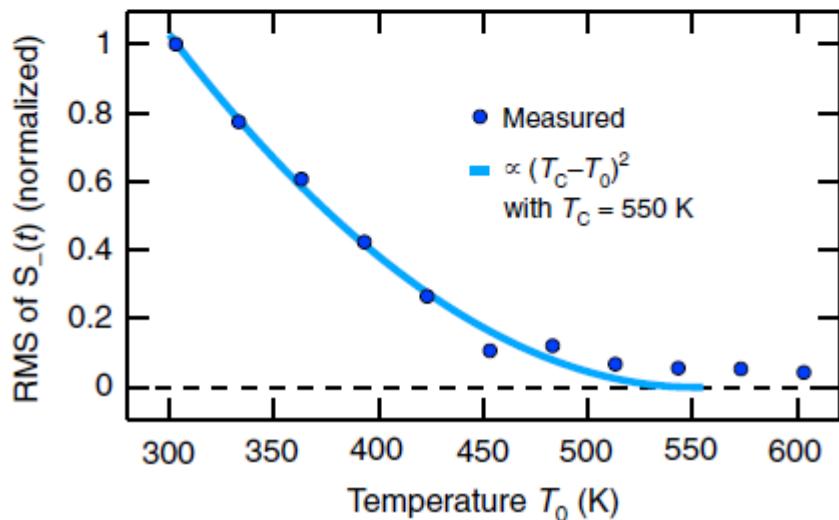
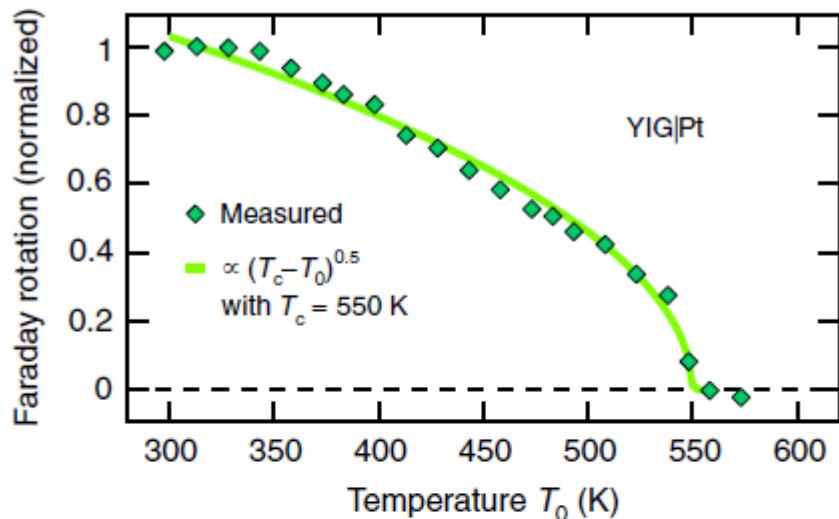


Seifert et al., Nature Comm. 2018



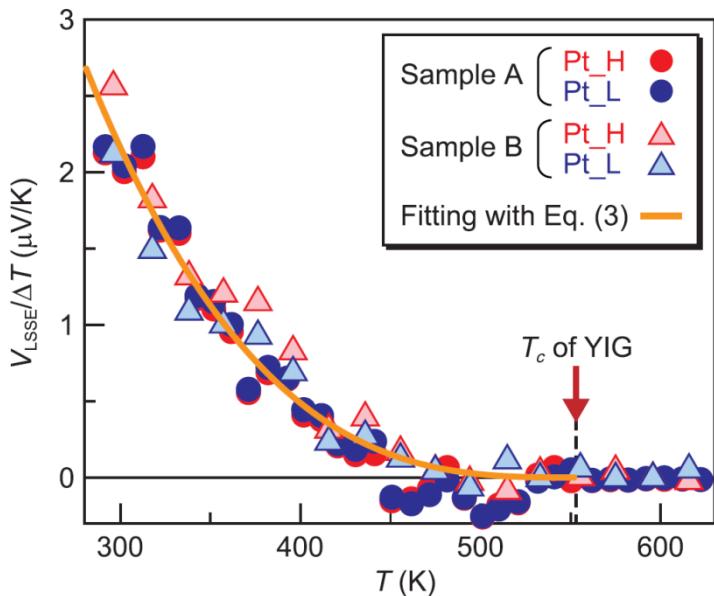
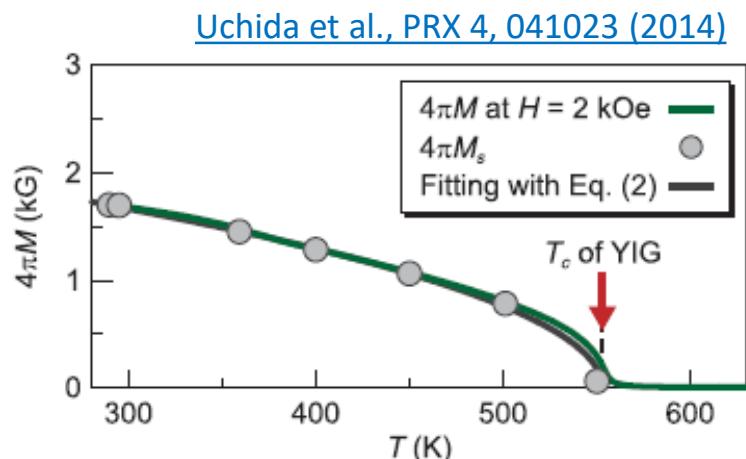
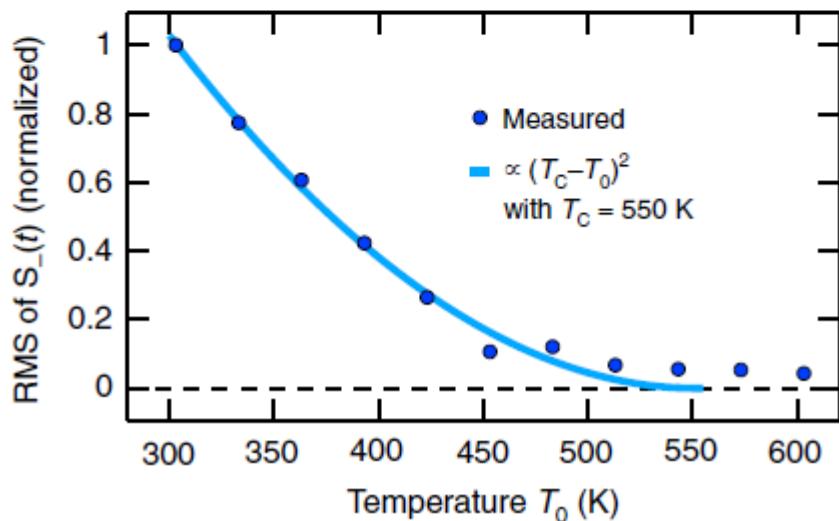
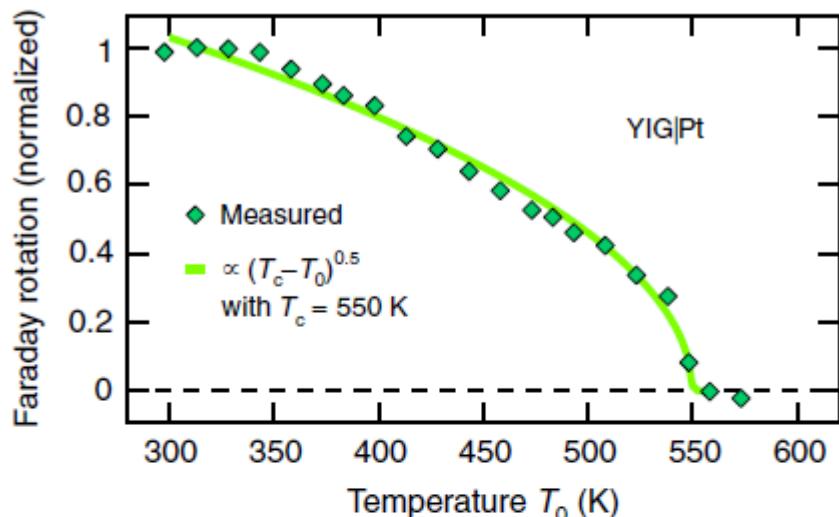
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Seifert et al., Nature Comm. 2018



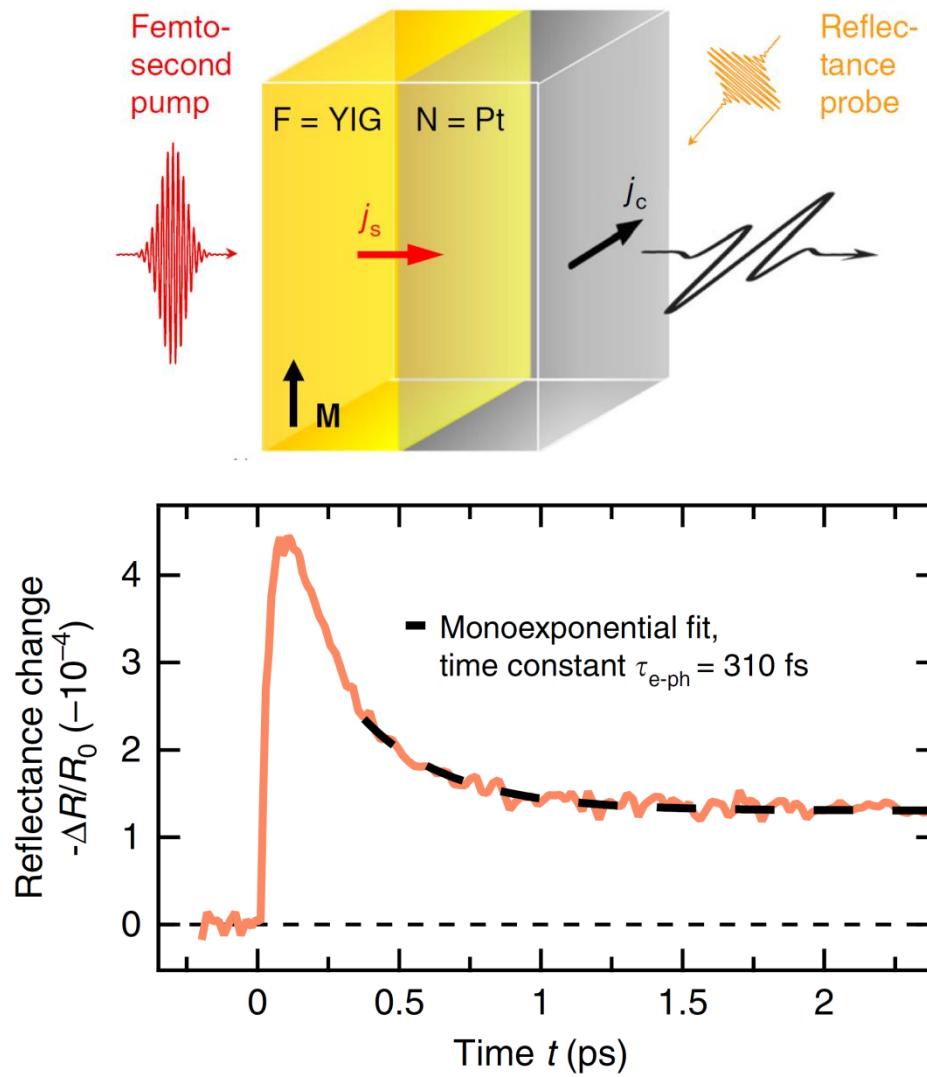
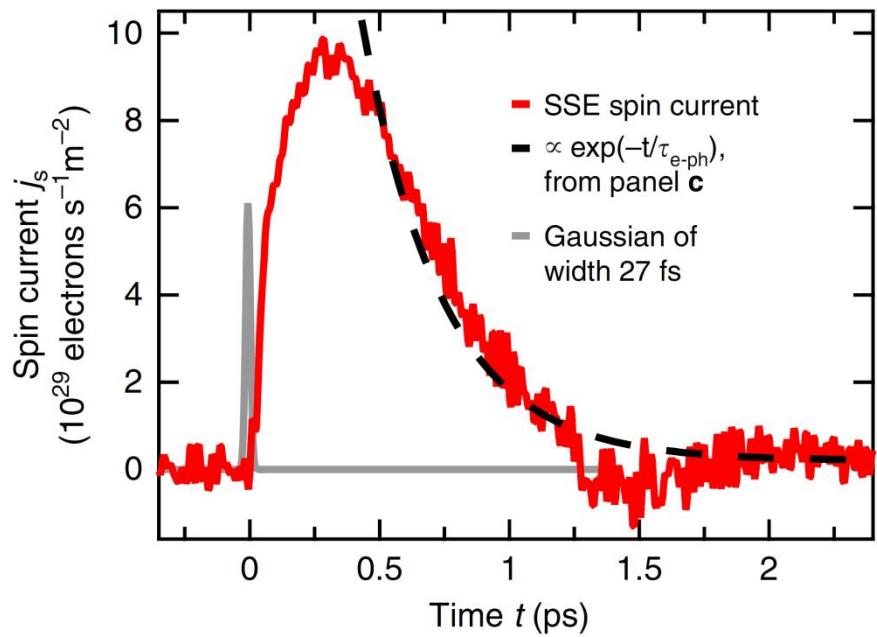
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Seifert et al., Nature Comm. 2018



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Seifert et al., Nature Comm. 2018



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THE WINTON PROGRAMME FOR THE
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