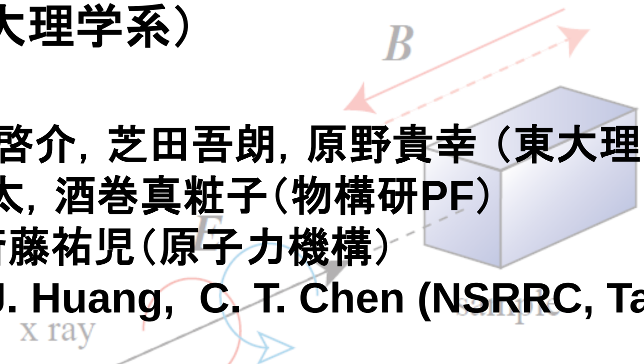
PF研究会「軟X線分光，散乱測定を用いた物性研究の現状と展望」
2011年9月13,14日

軟X線磁気円二色性による磁性ナノ構造の研究

藤森　淳（東大理学系）



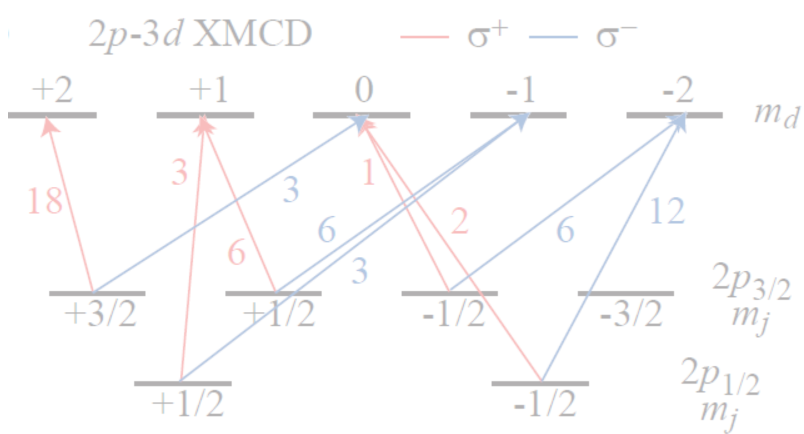
門野利治，V. R. Singh，V. K. Verma, 石上啓介，芝田吾朗，原野貴幸（東大理）
PF BL-16A2: 小出常晴，朝倉大輔，雨宮健太，酒巻真粧子（物構研PF）
SPring8 BL23-SU: 竹田幸治，岡根哲夫，斎藤祐児（原子力機構）
TLS BL-11A1: F. H. Chang, H.-J. Lin, D.-J. Huang，C. T. Chen (NSRRC, Taiwan)

$SrRuO_3$, $La_{1-x}Sr_xMnO_3$: 組頭広志（物構研PF），吉松公平，尾嶋正治（東大工）

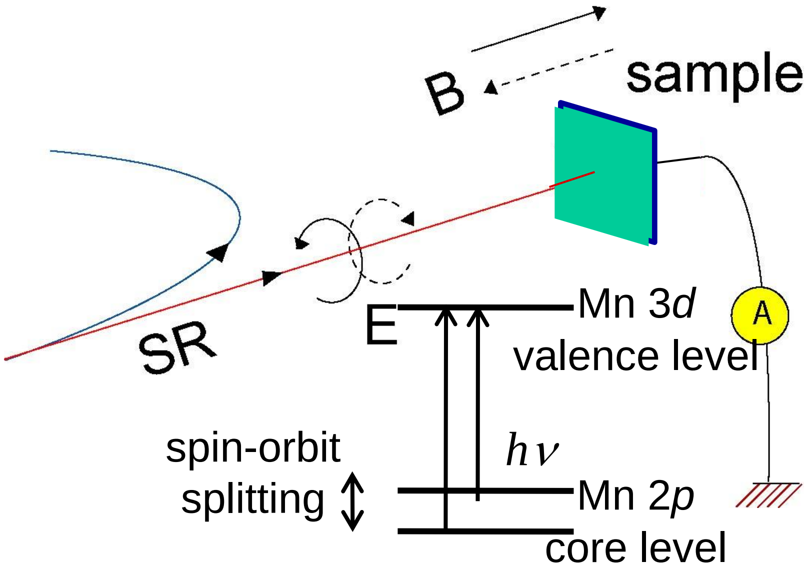
多重項計算，クラスター計算: 田中 新（広大先端物質）

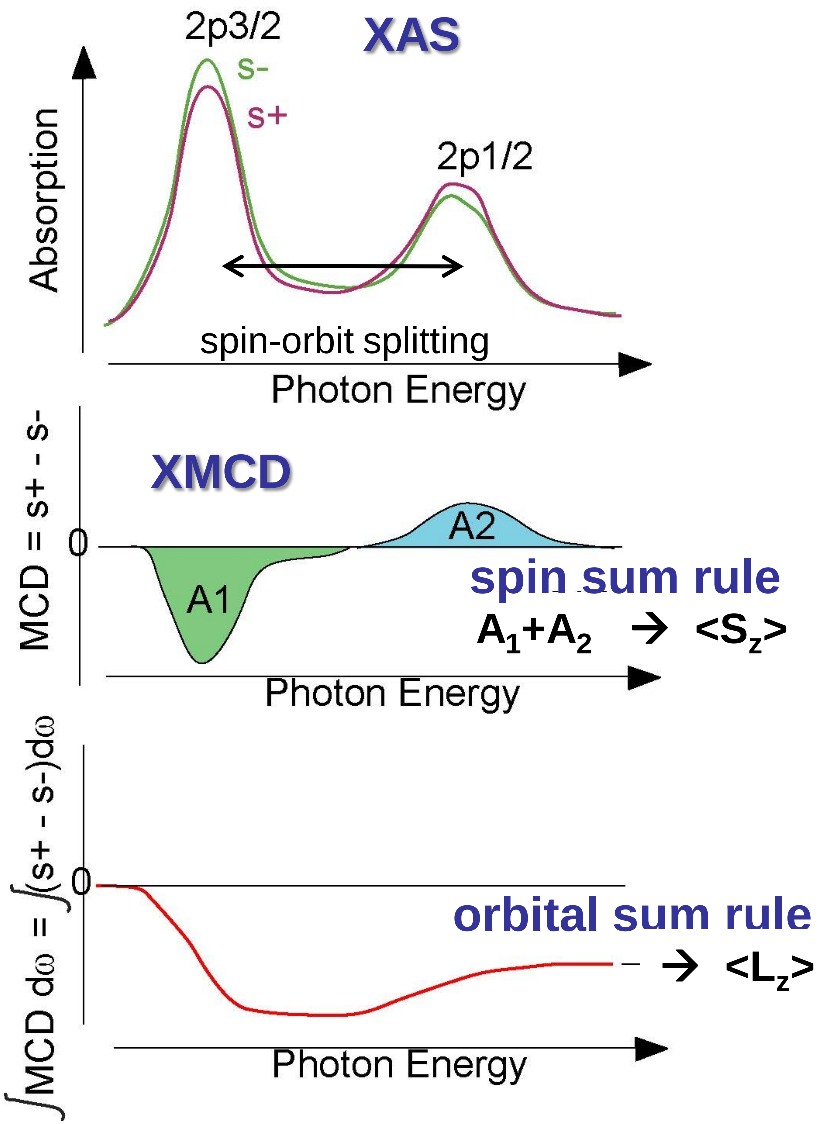
概要

- 測定原理，特徴
- これまでの研究例
  - ー希薄磁性半導体
  - ー酸化物薄膜
- 今後の展望



X-ray magnetic circular dichroism (XMCD) in core-level x-ray absorption spectroscopy (XAS)





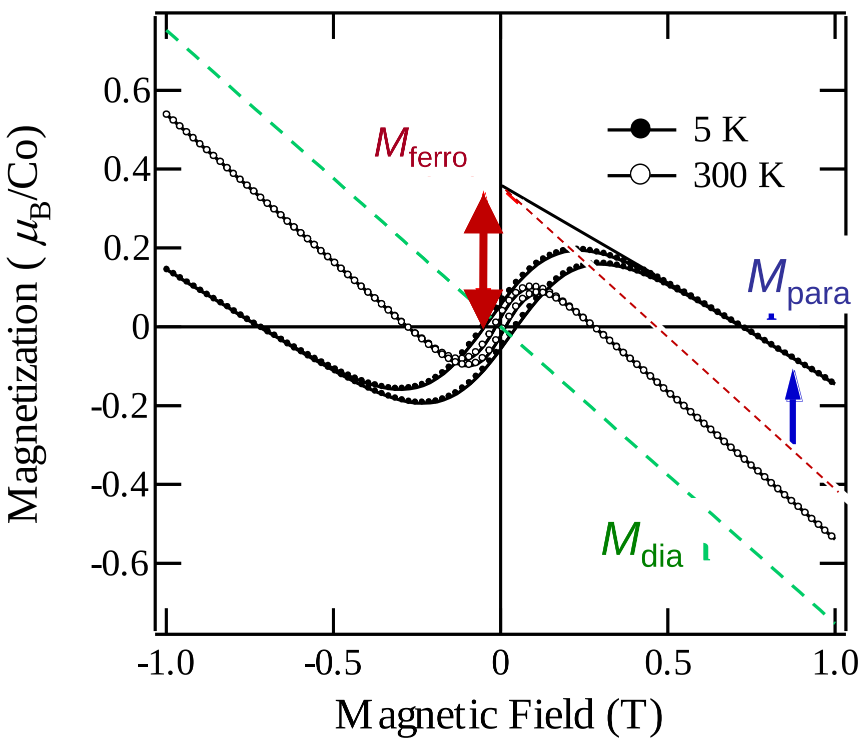
- **Element-specific**
- **chemical state-selective**
- **Magnetism-selective**

B. T. Thole et al., PRL '01, P. Carra et al., PRL '93

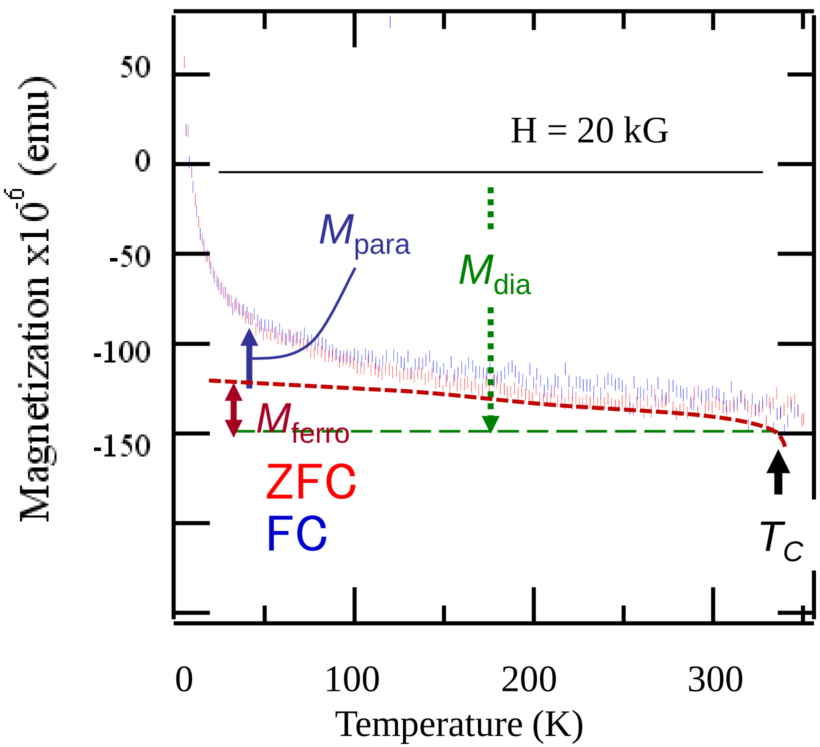
Ferromagnetic and paramagnetic components in magnetization and XMCD signals

SQUID data of thin film sample

M-H curve



M-T curve

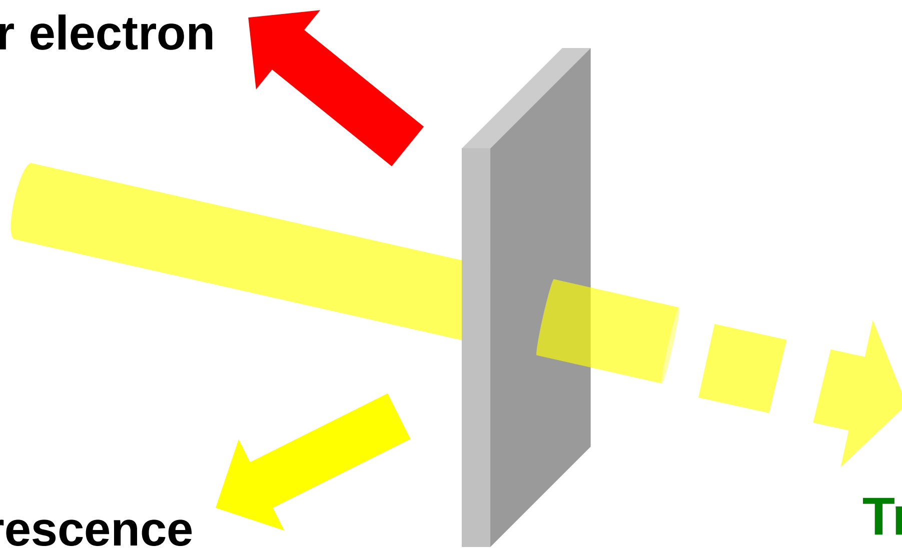


$M = M_{dia} + M_{ferro} + M_{para}$ → XMCD signals

Surface- and bulk-sensitive detection modes of XAS and XMCD measurements

Total electron yield (TEY) mode

probing depth ~ 3-5nm



Transmission mode

Bulk

Prohibited by ~mm thik substrate

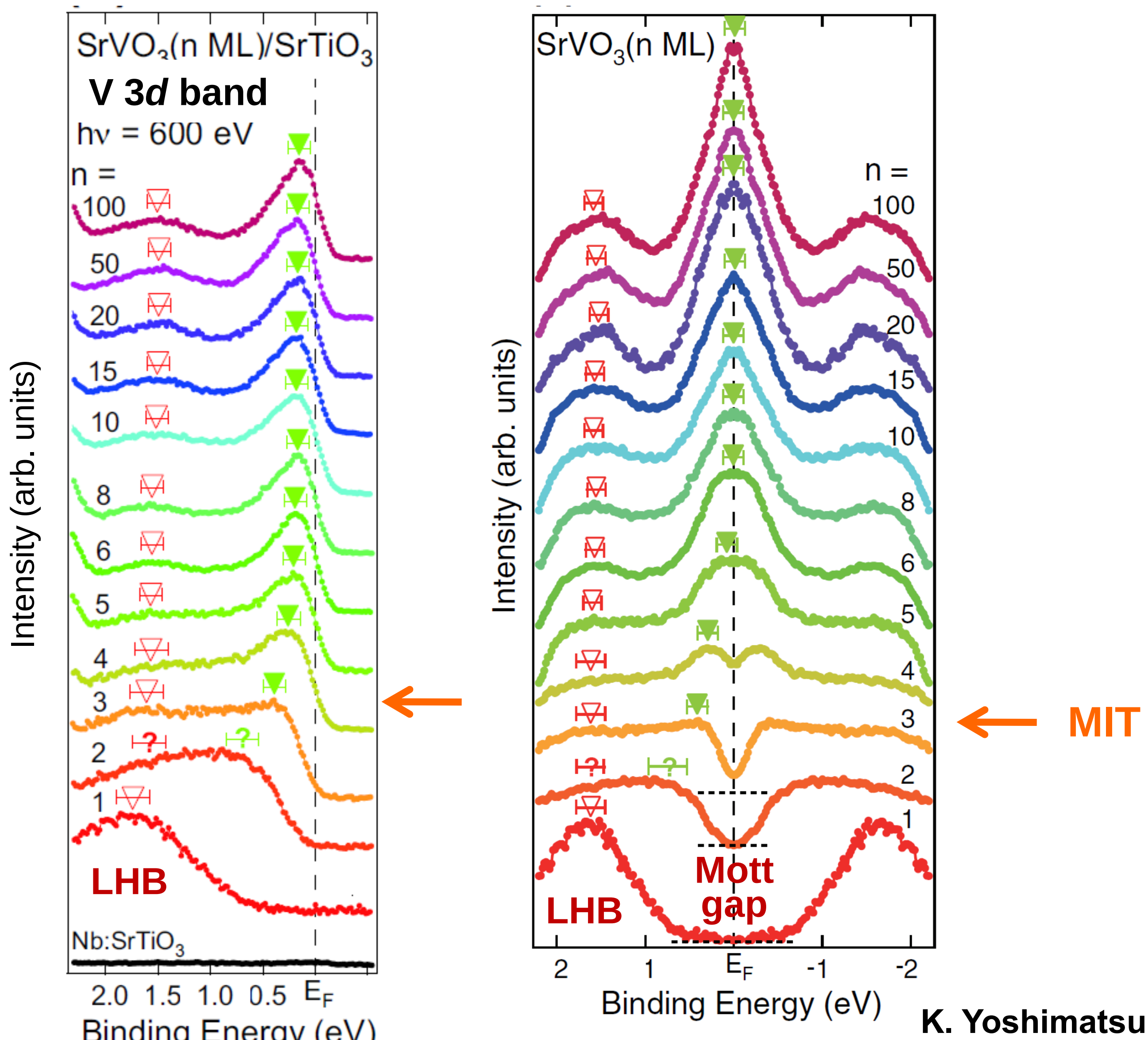
Total fluorescence yield (TFY) mode

probing depth ~ 100nm ~ film thickness

Disadvantage: Self-absorption → Partial fluorescence yield (PFY) mode

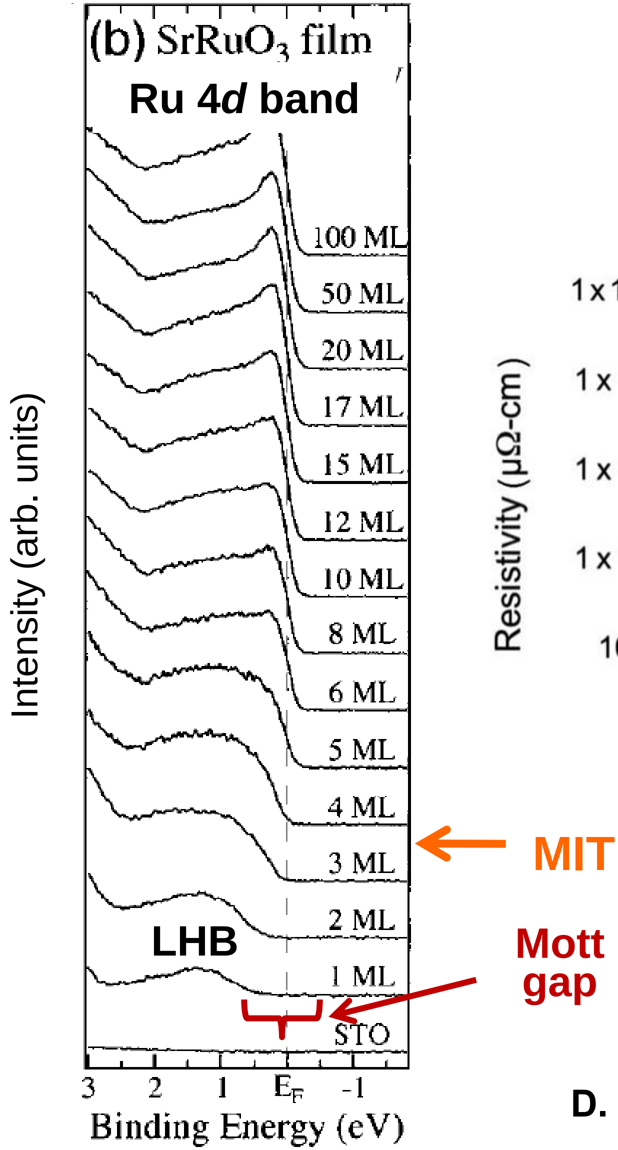
A. J. Achkar, PRB '11

Metal-to-insulator transition in $SrVO_3$ with decreasing film thickness



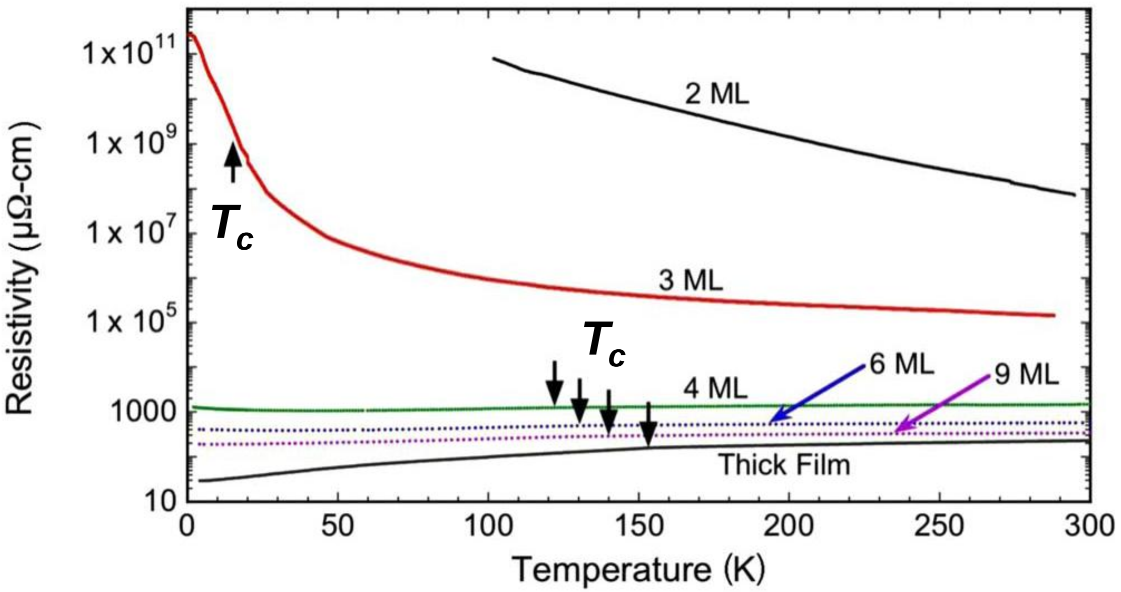
K. Yoshimatsu et al., PRL ’10

Metal-to-insulator transition in $SrRuO_3$ with decreasing film thickness



D. Toyota et al., APL '05

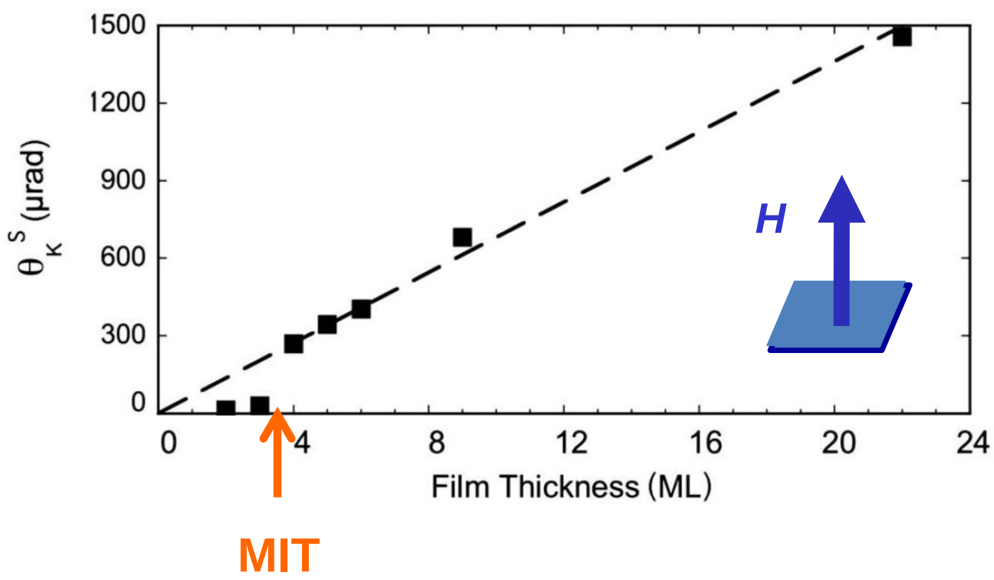
Resistivity



J. Xia et al., PRB '09

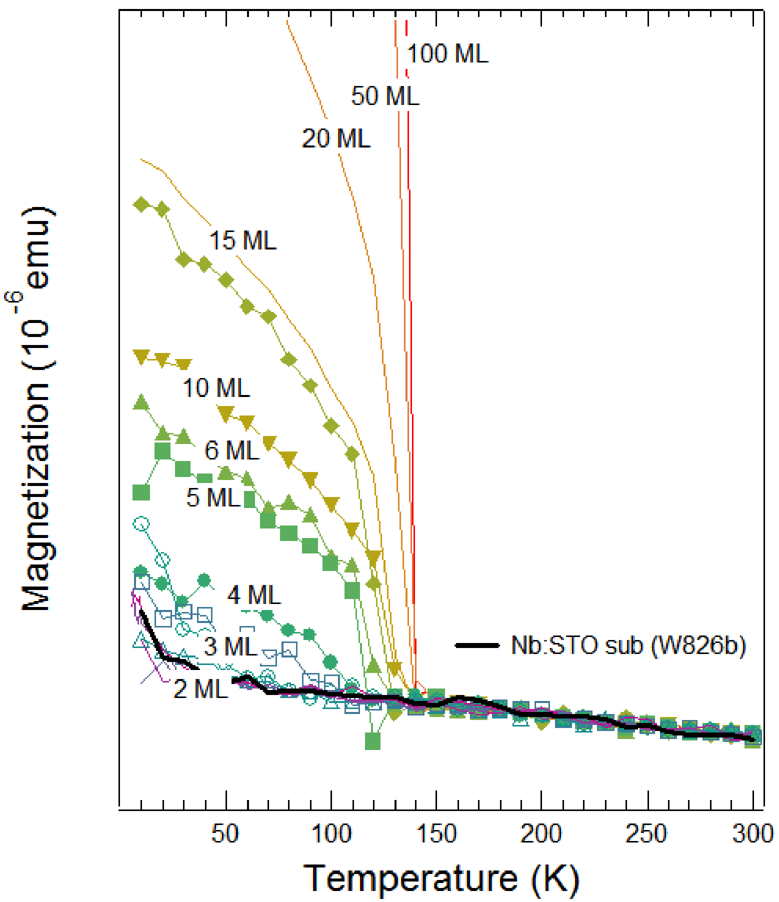
Concomitant ferromagnetic-to-paramagnetic transition in $SrRuO_3$ thin films

Polar Kerr effect



J. Xia et al., PRB '09

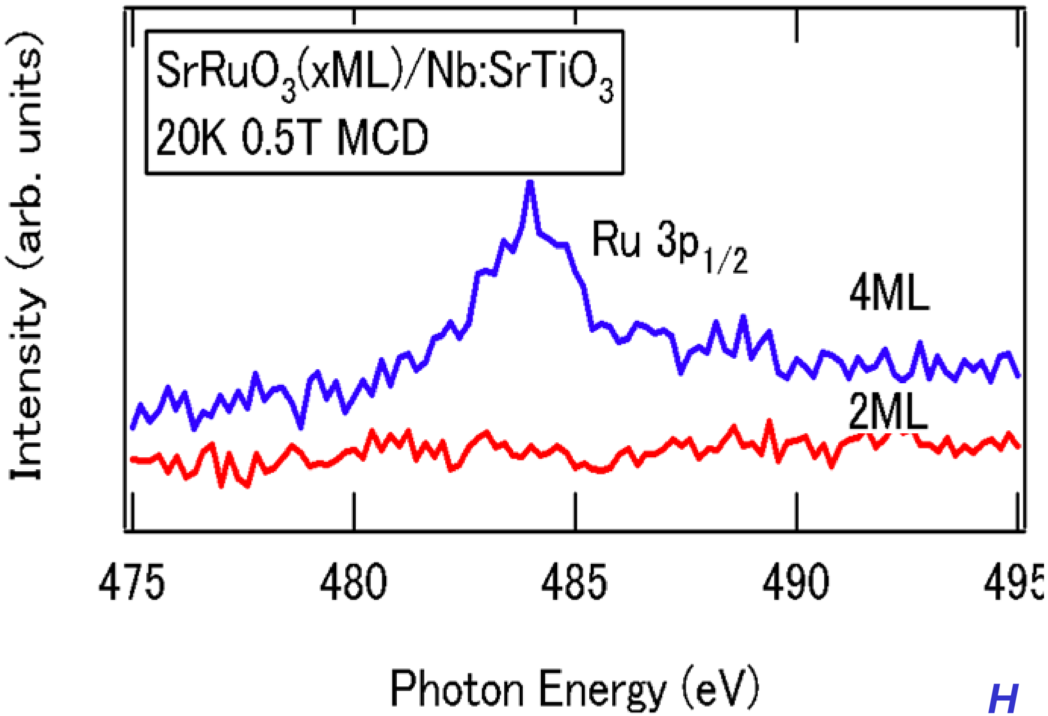
Magnetization measured by SQUID



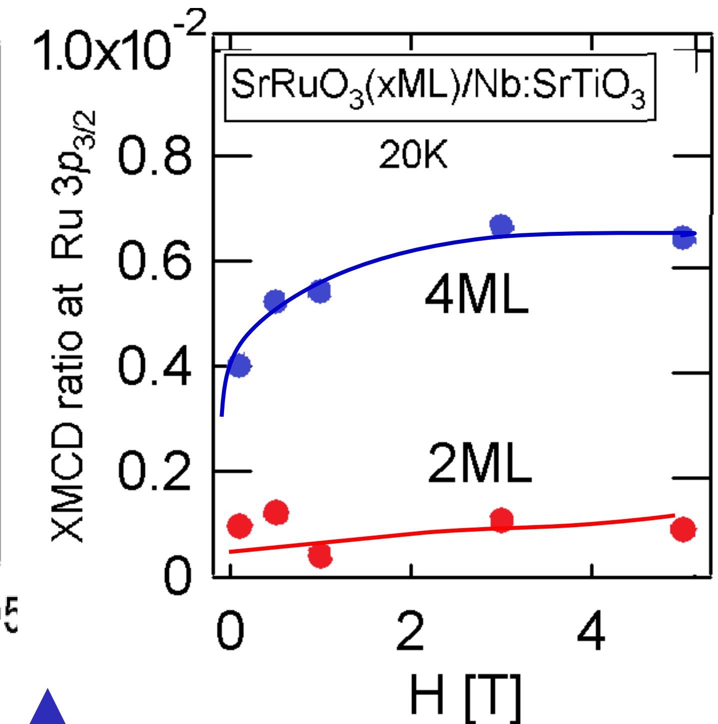
M. Takizawa et al.

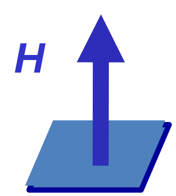
Ru 3*p* → 3*d* XMCD of $SrRuO_3$ thin films near critical thickness

XMCD spectra



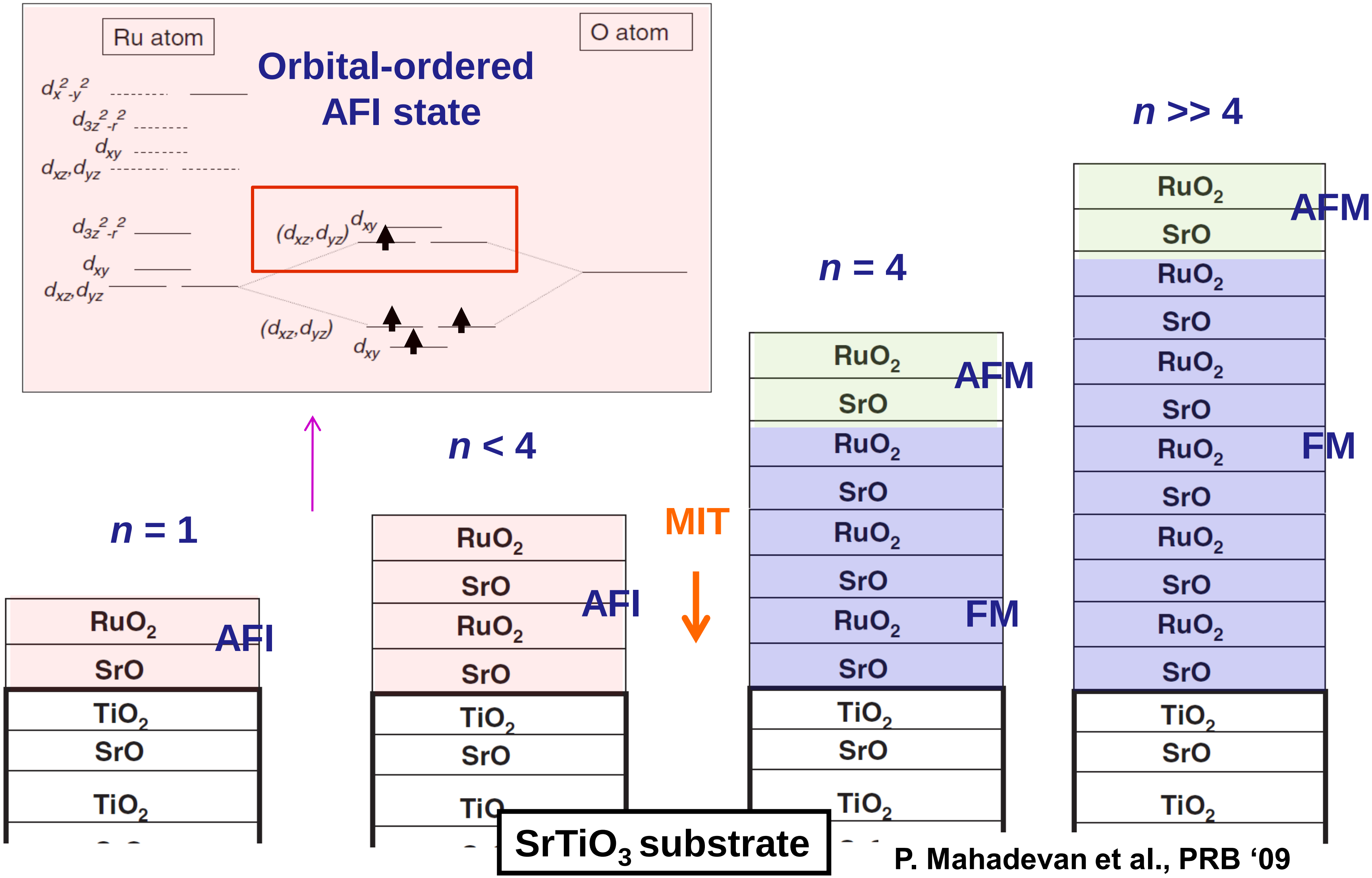
XMCD intensity *vs H*





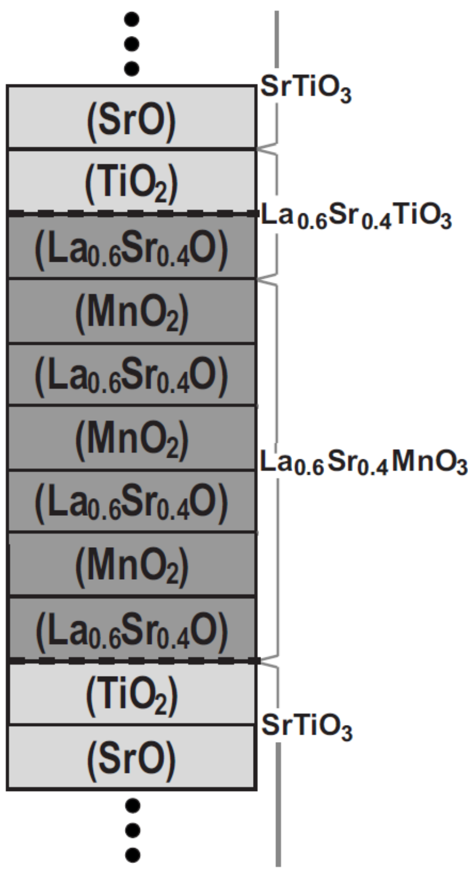
K. Ishigami et al.

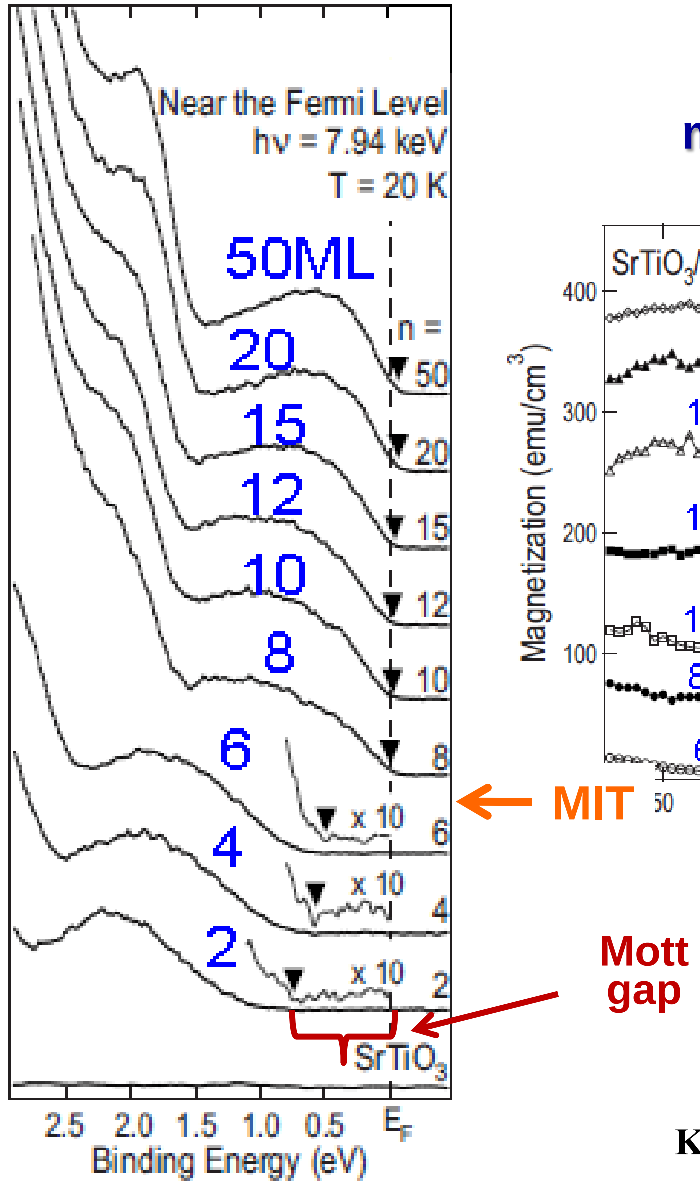
LDA+U calculation of $SrRuO_3$ thin films



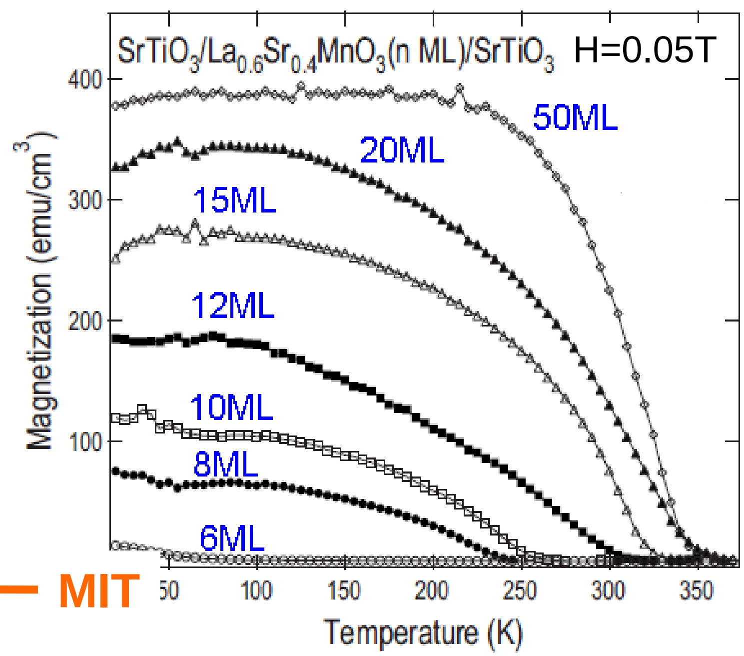
P. Mahadevan et al., PRB '09

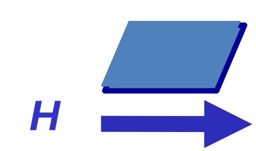
Metal-to-insulator transition in $La_{1-x}Sr_xMnO_3$ with decreasing film thickness





Magnetization measured by SQUID

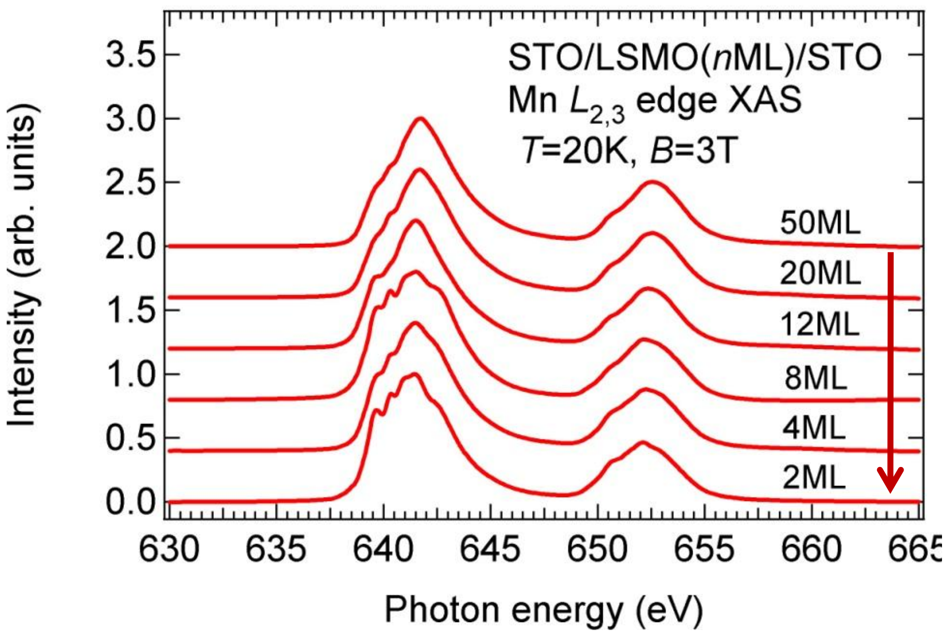




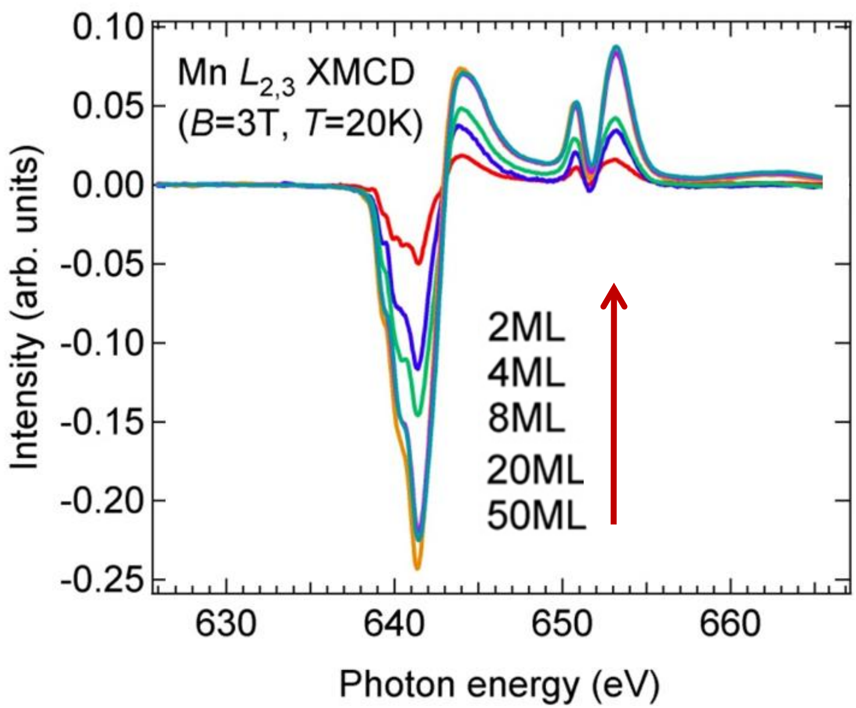
K. Yoshimatsu et al., APL '09

Mn 2*p*→3*d* XAS and XMCD of $La_{1-x}Sr_xMnO_3$ thin films

X-ray absorption spectroscopy (XAS) spectra



X-ray magnetic circular dichroism (XMCD) spectra

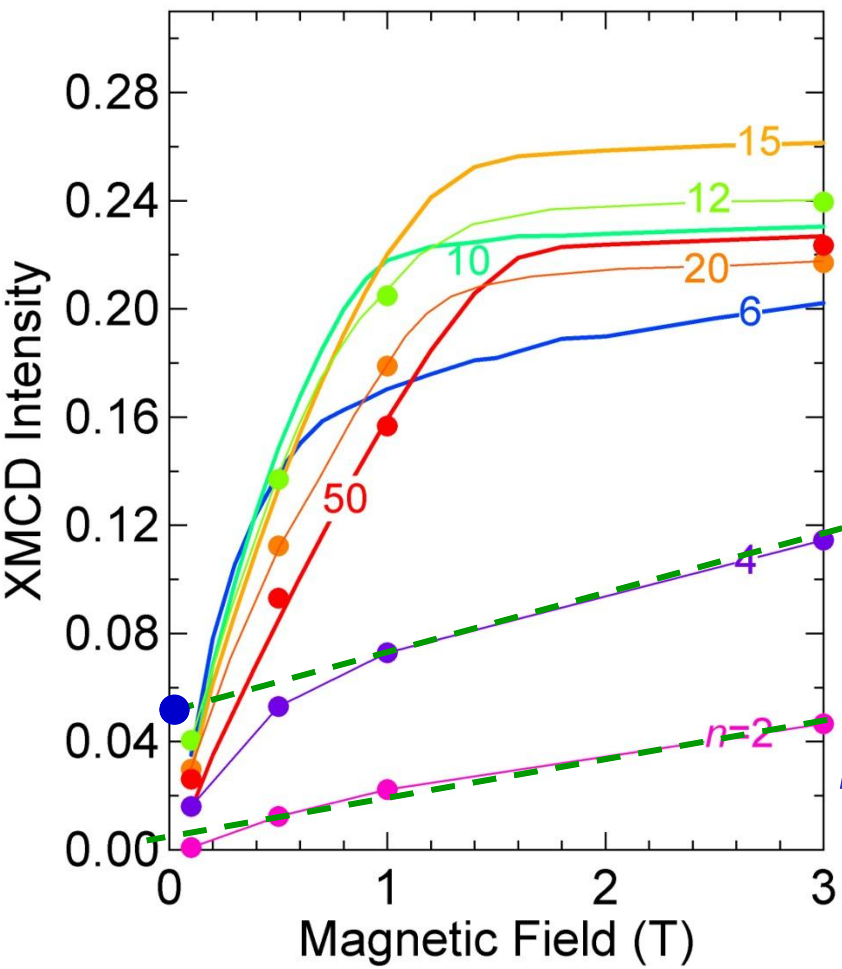


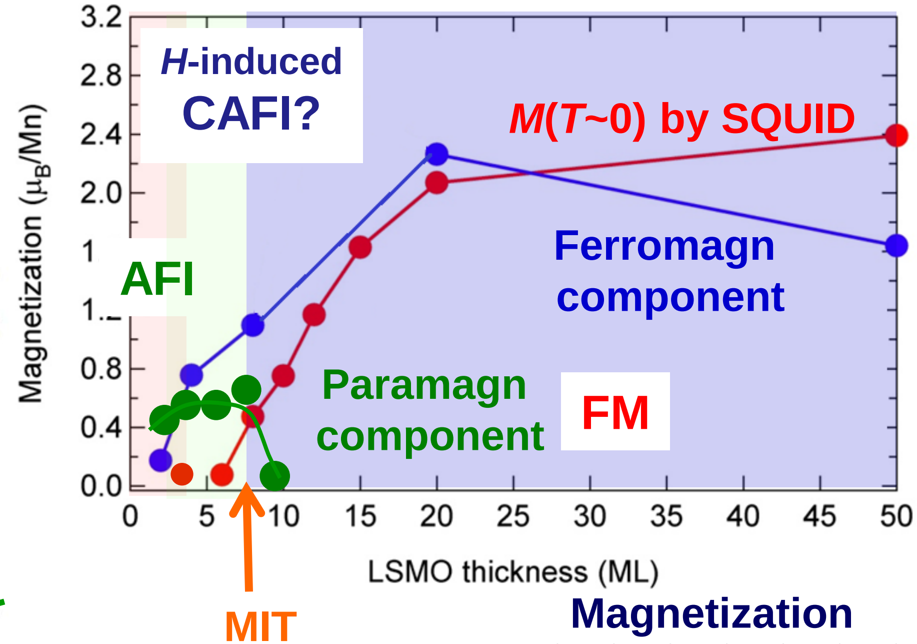
No change in Mn^{3+}/Mn^{4+} ratio

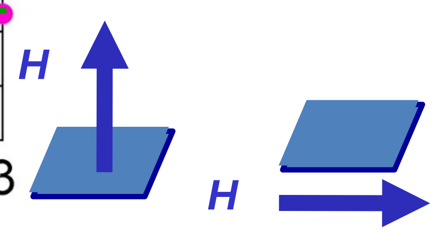
G. Shibata et al.

Mn 2p → 3d XMCD of $La_{1-x}Sr_xMnO_3$ thin films

XMCD intensity *vs H*

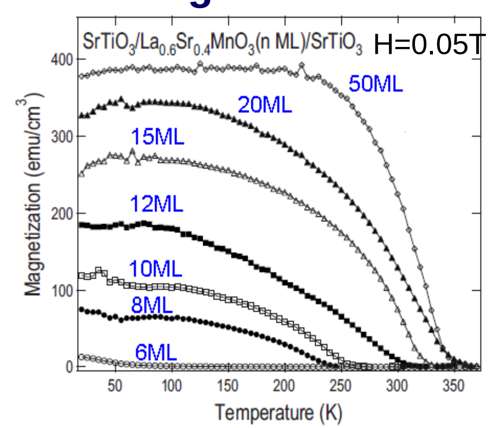






G. Shibata et al.

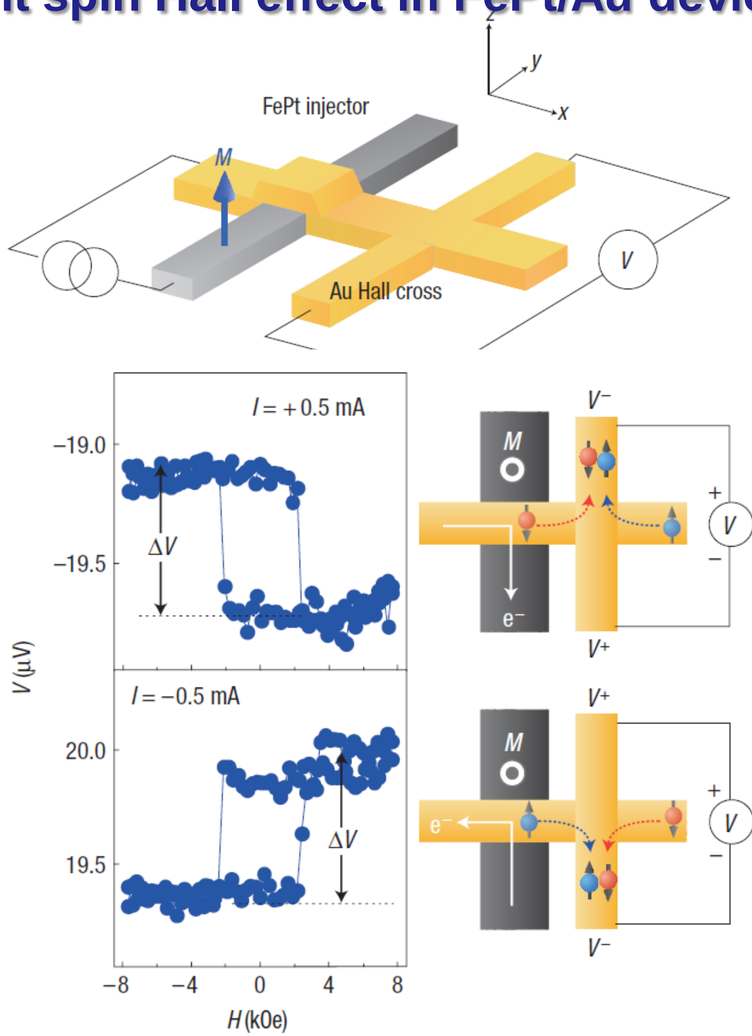
Magnetization



K. Yoshimatsu et al., APL '09

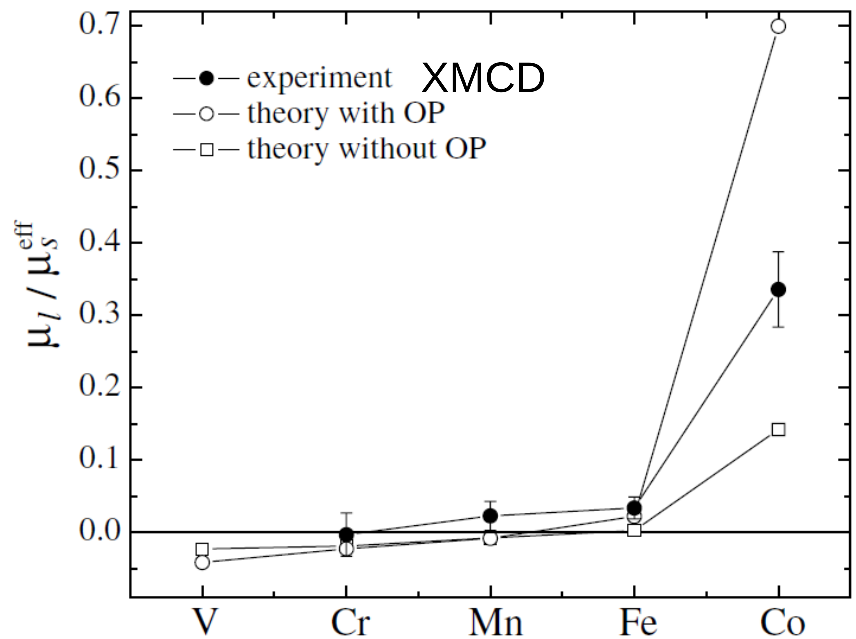
スピンホール系におけるスピン軌道相互作用

Giant spin Hall effect in FePt/Au devices



T Seki et al, Nat. mater. '08

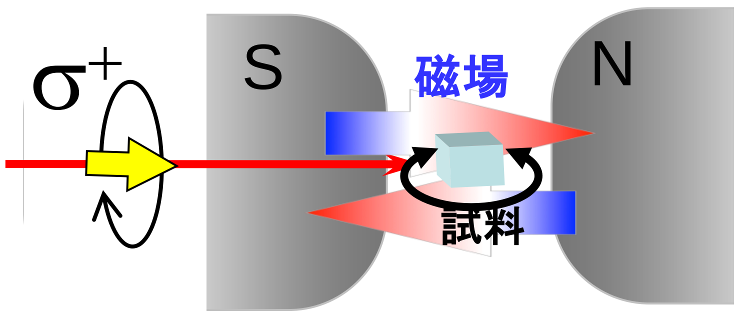
Orbital moment of TM atom in Au



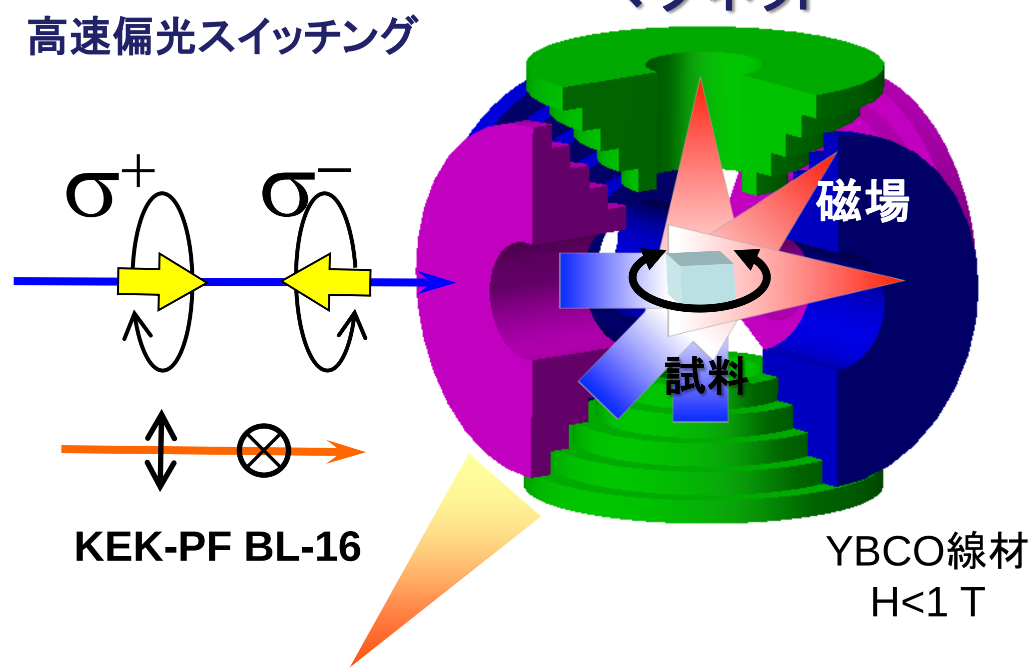
W. D. Brewer et al., PRL '04

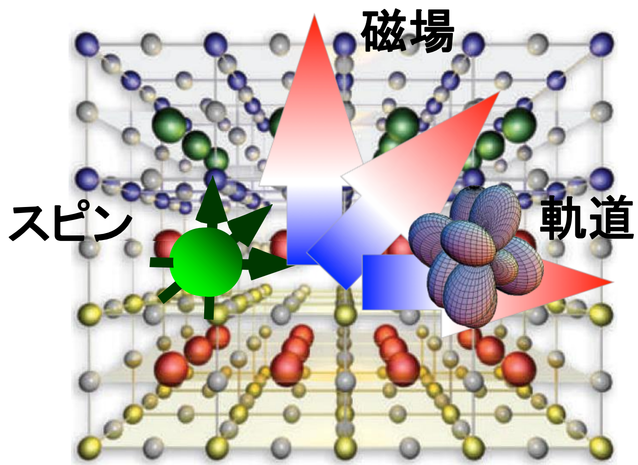
ベクトル型マグネットと高速偏光スイッチングを用いたXMCD

従来のXMCD装置



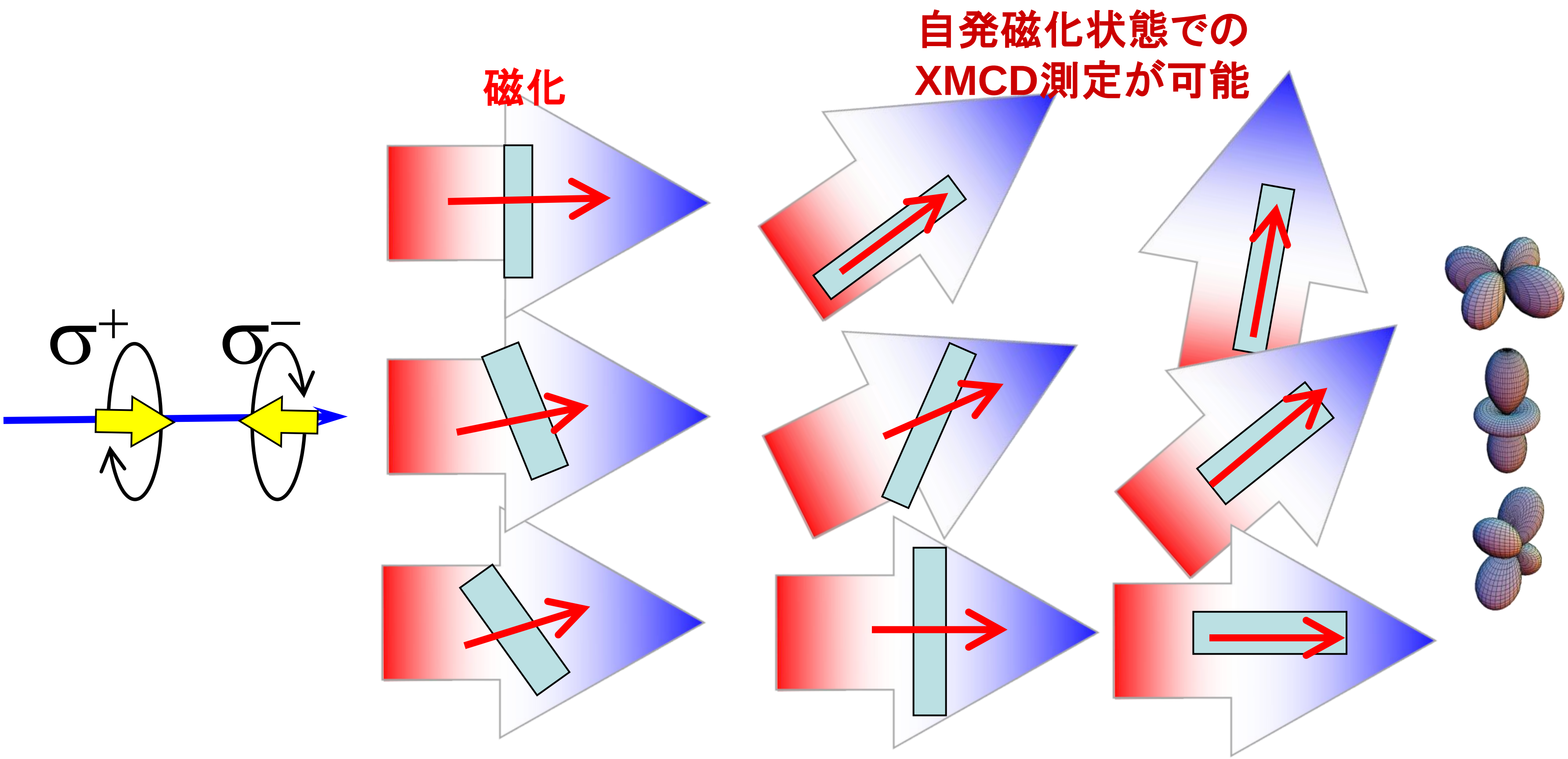
ベクトル型超伝導マグネット





- 磁気異方性
- スピン-軌道状態
- 相競合，相分離

方向可変磁場を用いたXMCD



磁場と偏光が同時回転
両者の効果が分離できない

従来のXMCD

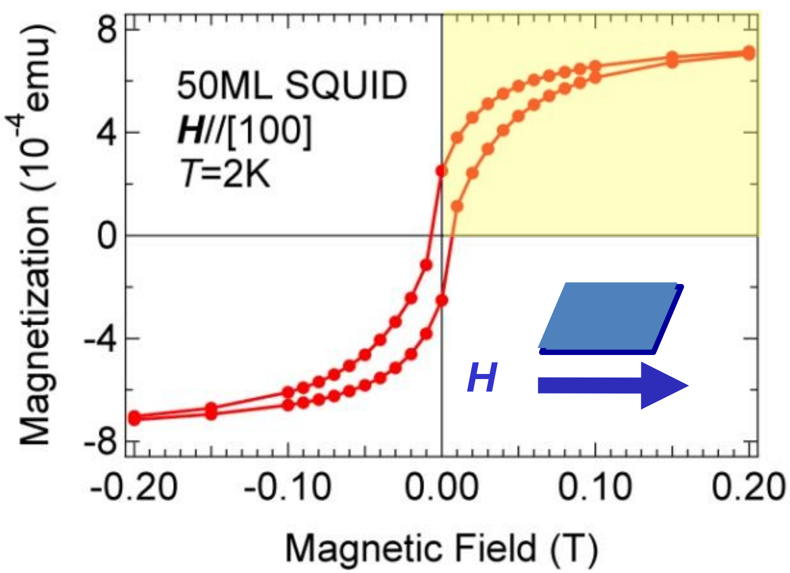
→ 磁気異方性

→偏光依存XMCD
→軌道依存磁気モーメント

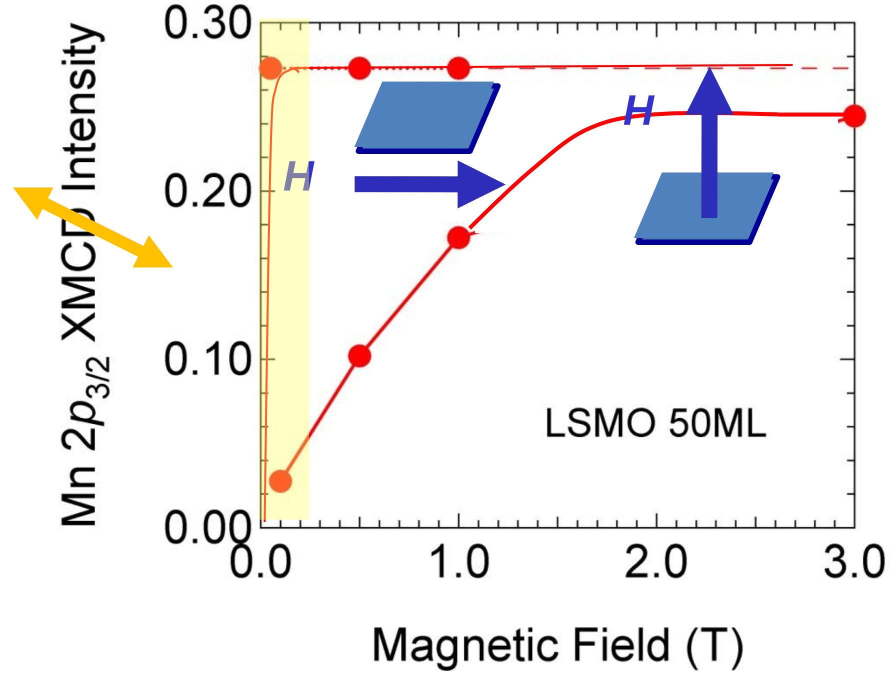
新XMCD装置

$La_{1-x}Sr_xMnO_3$薄膜の磁気異方性

Magnetization measured by SQUID



XMCD intensity *vs* *H*

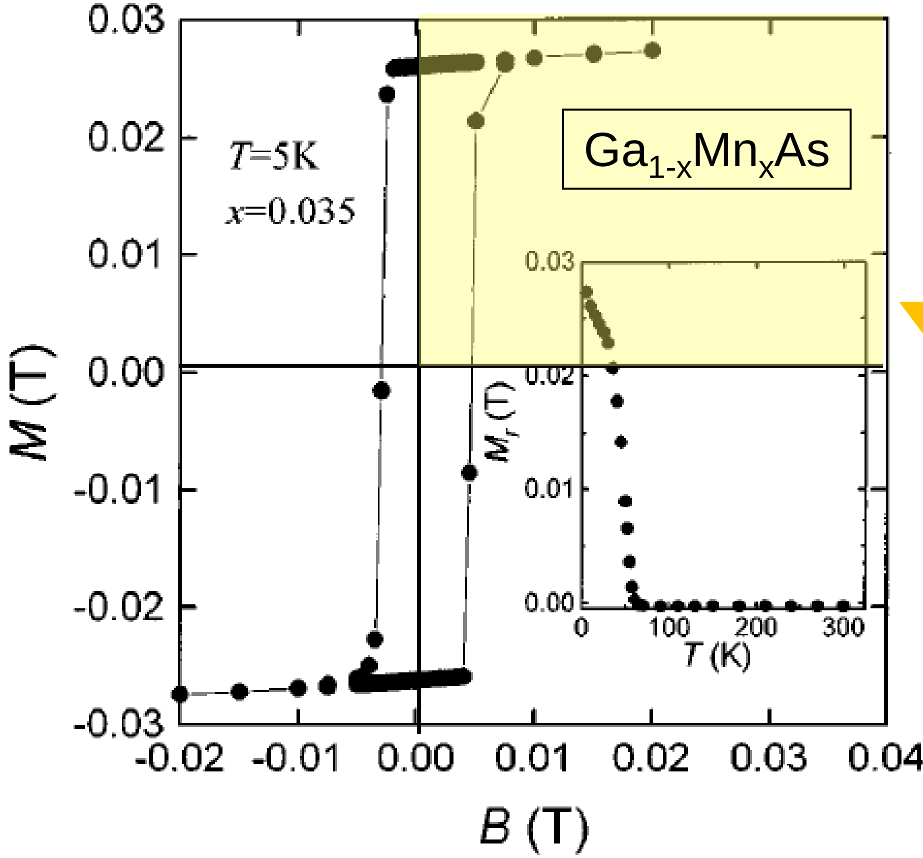


K. Yoshimatsu et al., APL '09

G. Shibata et al.

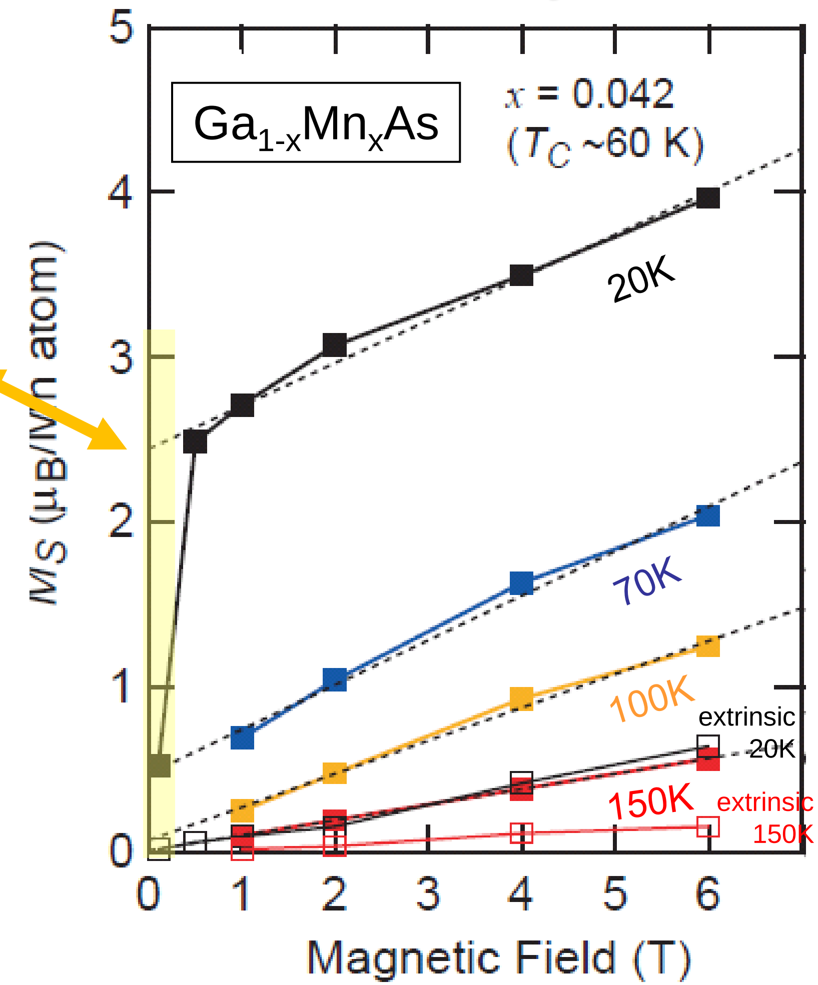
$Ga_{1-x}Mn_xAs$（薄膜試料）の磁気異方性

Magnetization measured by SQUID



H. Ohno e al. APL '96

XMCD intensity *vs H*

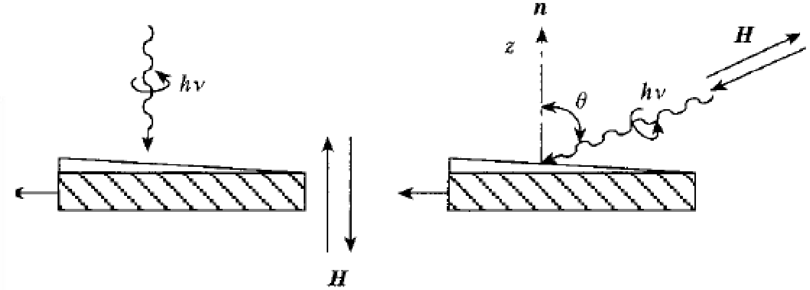


Y. Takeda et al. PRL '08

XMCDの角度依存性測定によるスピン・モーメントおよびスピン分布四重極モーメントの決定

偏光X線を用いた*d*軌道の異方性の検出

Orbital i	$\alpha = x, y$ or z $4\left(7\langle Q^i_\alpha \rangle\right)$	Linear Pol. $\vec{E} \parallel \alpha$ $4\left(1-\frac{7}{4}\langle Q^i_\alpha \rangle\right)$	Circular Pol. $\vec{k} \parallel \alpha$ $4\left(1+\frac{7}{8}\langle Q^i_\alpha \rangle\right)$	Circ. Dichroism $\vec{k}, \vec{H}_{ext} \parallel \alpha$ $4\left(1+\frac{7}{2}\langle Q^i_\alpha \rangle\right)$
d_{yz}	−8, −8, 16	6, 6, 0	3, 3, 6	0, 0, 12
d_{zx}	−8, 16, −8	6, 0, 6	3, 6, 3	0, 12, 0
$d_{3z^2-r^2}$	−16, 8, 8	8, 2, 2	2, 5, 5	−4, 8, 8
d_{xy}	16, −8, −8	0, 6, 6	6, 3, 3	12, 0, 0
$d_{x^2-y^2}$	16, −8, −8	0, 6, 6	6, 3, 3	12, 0, 0



$$m_{\rm orb}^{\theta} = -\frac{4}{3}\left[\frac{\Delta I_{L_3} + \Delta I_{L_2}}{I_{L_3} + I_{L_2}}\right]_{\theta} n_{\rm h}\mu_{\rm B}$$

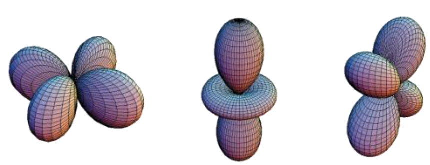
$$m_{\rm spin} - 7\, m_T^{\theta} = -2\left[\frac{\Delta I_{L_3} - 2\Delta I_{L_2}}{I_{L_3} + I_{L_2}}\right]_{\theta} n_{\rm h}\mu_{\rm B}$$

$$m_T^{\perp} + 2 m_T^{/\!/} = 0$$

$$m_{\rm orb}^{\theta} = m_{\rm orb}^{\perp}\cos^2\theta + m_{\rm orb}^{/\!/}\sin^2\theta$$

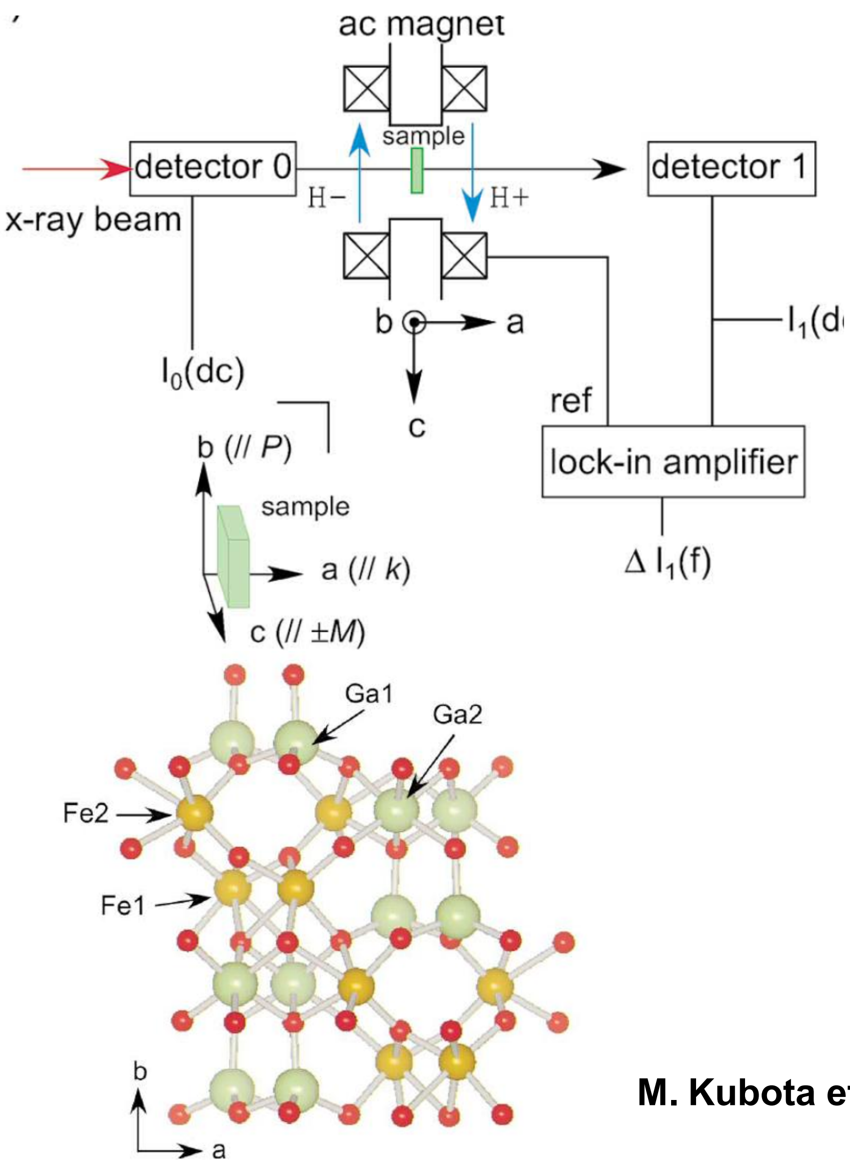
$$m_T^{\theta} = m_T^{\perp}\cos^2\theta + m_T^{/\!/}\sin^2\theta$$

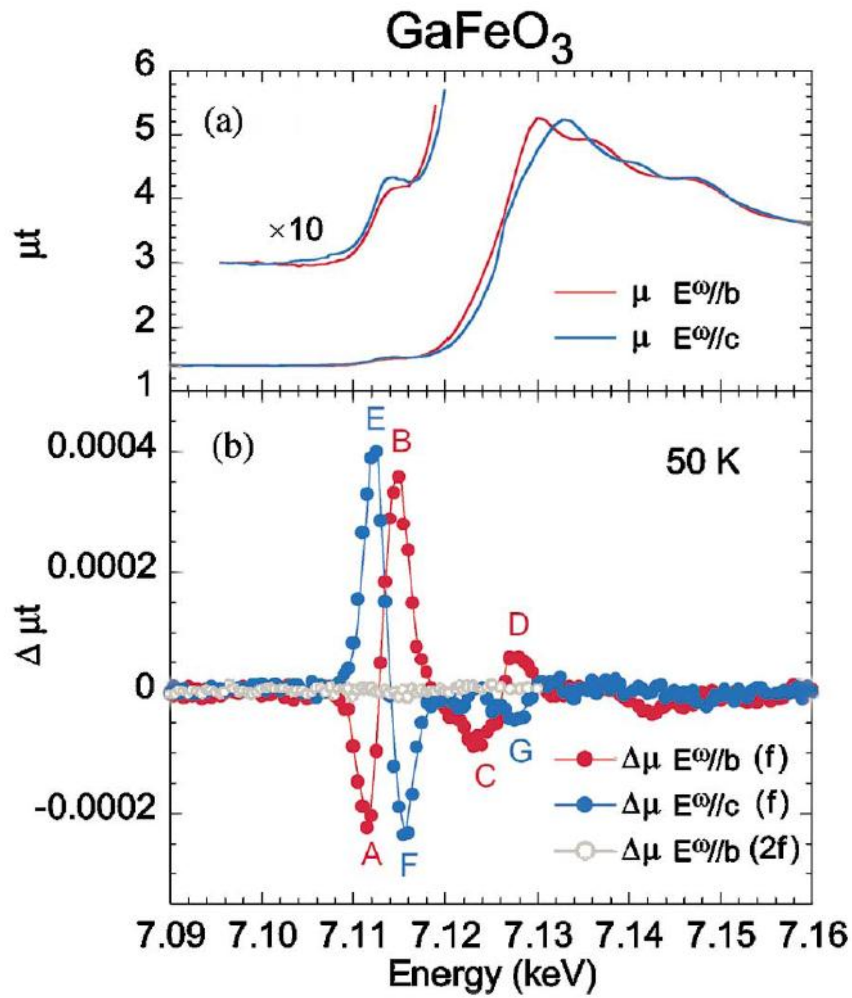
→ $m_{\rm spin}$, $m_{\rm orb}^{\theta}$, m_T^{θ}の完全決定(θ=⊥,//)



小出常晴:「新しい放射光の科学」
菅野，藤森，吉田編（講談社2000年）

軟X線非相反方向二色性(XNDD)の測定





M. Kubota et al., PRL ‘04

まとめ

- 研究対象
  - 希薄磁性半導体
  - 磁性薄膜： 厚さ依存，界面，表面，基板圧力，電場，．．．
  - 磁性ナノ構造： 細線，ナノワイヤー，ナノ粒子．．．
  - マルチフェロイック系，スピンホール系
- 今後の発展
  - 磁場方向依存 → 磁気異方性（希土類磁石？）
  - 偏光依存
  - 強磁場
  - 時間分解
- 他の手法との組み合わせ
  - 共鳴軟X散乱
  - ．．．．