Crystal Orientation Dependence of X-ray Magnetic Linear Dichroism in Altermagnetic RuO₂

Jun Okabayashi,[1*] Zhenchao Wen,[2] Yoshio Miura,[3,2] Hiroaki Sukegawa,[2] and Seiji Mitani[2]

[1]*Research Center for Spectrochemistry, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2]*Research Center for Magnetic and Spintronic Materials, National Institute for Materials Science (NIMS), Tsukuba, Ibaraki 305-0047, Japan*
[3]*Kyoto Institute of Technology, Kyoto 606-8585, Japan*

[*]E-mail: jun@chem.s.u-tokyo.ac.jp

Altermagnetism has recently been developed using time-reversal symmetry breaking spintronics and spin-splitting phenomena in materials with collinear-compensated magnetic order [1]. It arises from the unique band structures that split up and down spin bands, which differs from ferromagnetic exchange splitting and antiferromagnetic compensation. Some materials, such as RuO_2, MnTe, and CrSb, have been classified as exhibiting altermagnetism. In particular, RuO_2 features unique spin-dependent elliptical Fermi surfaces, which are regarded as the origin of the spin-splitting effect [2]. However, a recent topical issue regarding altermagnetism in RuO_2 is the existence or absence of magnetic moments at the Ru sites. Although recent μSR measurements for bulk RuO_2 reported the absence of magnetic moments [3], the RuO_2 film includes local strain, which might be essential for the presence of finite Ru magnetic moments and altermagnetic properties. To address these controversial issues, we employ x-ray magnetic linear dichroism (XMLD), which probes the square of the magnetization. The x-ray magnetic circular dichroism (XMCD) is ineffective for detecting compensated spins. Thus far, we have examined the angular-dependent XMLD for RuO_2 (101) to determine the Néel vector direction along [001] with finite magnetic moments at each Ru site [4]. In this presentation, to further understand the details of the magnetic structures of RuO_2, we performed XMLD for other (110) orientation planes.

We prepared a sample of a 20-nm-thick rutile-type RuO_2 (101) layer and a RuO_2 (110) layer, both conductive, grown on single-crystal $Al_2O_3(1\bar{1}02)$ substrates and TiO_2 (110) substrates, respectively, using reactive rf-sputtering. The Néel temperature of the sample was determined to be approximately 400 K. The magnetic moments in RuO_2 are aligned along the [001] direction. The direction of the Néel vector was established from previous angular-dependent XMLD measurements [4]. XMCD and XMLD measurements for the Ru *M*-edge were conducted at BL-7A and BL-16A in the Photon Factory (KEK). The total-electron-yield mode was employed at 80 K. For the XMLD, horizontally and vertically linearly polarized beams were directed into the sample, and the difference is defined as linear dichroism.

The x-ray absorption spectra in the 4*d* transition-metal element *M*-edge consist of not only 3*p* to 4*d* transitions but also 3*p* to 5*s* transition peaks. There was no XMCD signal due to complete compensation in the total magnetization (M). To detect M^2, XMLD was performed with strong coupling geometry between the electric field in the incident beam and the Néel vector in the sample. For the RuO_2 (110) plane, the Néel vector aligns along the in-plane [001] direction. XMLD signals are clearly detected, and by rotating the sample position in the plane, the sign of XMLD changes, suggesting a change in the Néel vector. These observations indicate that the magnetic moments at the Ru sites align along the Néel vector. M^2 intensities are nearly identical to those of RuO_2 (101), suggesting that finite magnetic moments can form for both orientations.

References: [1] L. Šmejkal *et al*., Phys. Rev. X **12**, 040501 (2022).   [2] S. Karube *et al*., Phys. Rev. Lett. **129**, 137201 (2022).
[3] M. Hiraishi *et al*., Phys. Rev. Lett. 132, 166702 (2024).   [4] C. He, Z. Wen, J. Okabayashi *et al*., submitted.