Atomic scale magnetic and structural imaging by achromatic electron microscopy

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The atomic-level knowledge of local spin configuration of the magnetic materials is of great importance to predict and control their physical properties, in order to meet the challenges of ever-increasing demands on performance of functional materials. However, it is highly challenging to experimentally characterize magnetic properties of such materials with atomic scale spatial resolution. Our study demonstrates a breakthrough in the ability to provide direct real-space insight into magnetic spins in materials at the atomic scale[1]. This information is important on a fundamental level in physics, materials science and nanotechnology, as well as for applications such as new designs of energy-efficient spintronic devices, in which the local interplay between charge, spin, orbital and lattice degrees of freedom is currently inaccessible experimentally.

The best option to push the spatial resolution of the spectromicroscopies lies in the electron beam equivalent technique electron energy-loss magnetic chiral dichroism (EMCD) [2], which is also called electron magnetic circular dichroism. Physically, X-ray magnetic circular dichroism (XMCD) and EMCD shares the same underlying physics in which the angular momentum transferred during X-ray absorption or inelastic electron scattering can selectively excite magnetic sublevels in atoms. The structured electron beams generated through interference of suitably phased plane waves can produce beams with orbital angular momentum. In principle EMCD can offer higher spatial resolution and greater depth sensitivity due to the short de Broglie wavelength and penetration of high-energy electrons compared to XMCD. Previously, we have found a strong EMCD signal in transition metal oxides allowing them to use standing wave methods to identify the different spin states of Fe atoms with site specificity [3].

Our approach combines spatially-resolved EMCD with the latest developments in chromatic aberration corrected electron microscopy, which reduces the focal spread of inelastically scattered electrons by orders of magnitude when compared with the use of spherical aberration correction alone. Magnetic circular dichrosim spectra have been imaged atomic plane by atomic plane for the double perovskite Sr_2FeMoO_6, which can provide quantitative information of element-selective orbital and spin magnetic moments at the atomic level[1]. The spatial resolution of atomic-plane resolved EMCD method goes beyond that of any currently available technique, including XMCD and neutron diffraction. It is applicable to studies of spin configurations, atomic structure and chemical bonding at different magnetically coupled interfaces, including magnetic spring effects at interfaces between hard and soft magnets, magnetoelectric coupling between ferromagnetic and ferroelectric materials and exchange bias between antiferromagnetic and ferromagnetic materials.

Reference

1. Z. C. Wang, A. H. Tavabi, L. Jin, J. Rusz, D. Tyutyunnikov, H. B. Jiang, Y. Moritomo, J. Mayer, R. E. Dunin-Borkowski, R. Yu, J. Zhu and X. Y. Zhong*. Atomic scale imaging of magnetic circular dichroism by achromatic electron microscopy. *Nature Materials* **17**, 221-225, (2018).
2. Schattschneider, P. *et al.* Detection of magnetic circular dichroism using a transmission electron microscope. *Nature* **441,** 486 - 488 (2006).
3. Z. Q. Wang, X. Y. Zhong*****, R. Yu, Z. Y. Cheng, J. Zhu*, Quantitative experimental determination of site-specific magnetic structures by transmitted electrons. *Nature Communications***, 4**, 1395, (2013).

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