Photocontrol of magnetic and electronic structures in antiferromagnetic Dirac semimetals

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Antiferromagnets are promising systems for spintronics owing to the robustness against a perturbative field and the higher energy scale compared with that of ferromagnets. One of the ways to control the staggered magnetization (Néel vector) in the antiferromagnets is to utilize the Néel spin-orbit torque (SOT) generated by an electric current through a spin-orbit coupling [1]. However, although a lot of effort has been devoted to the study of the electrical switching of the antiferromagnets, it is not fully investigated whether and how the Néel SOT is generated by optically-induced electric currents.

A topological semimetal candidate, CuMnAs, has the parity-time symmetry while each of the space-inversion symmetry and the time-reversal symmetry is broken in the antiferromagnetic phase. This guarantees the two-fold (Kramers) degeneracy in the whole Brillouin zone. In particular, when the Néel vector is parallel to the $\langle 100 \rangle$ direction, a nonsymmorphic symmetry protects Dirac nodal lines at the Brillouin-zone boundary; thus this material is expected to be a Dirac semimetal. Šmejkal *et al.* proposed the minimal effective model on the square lattice given by the Hamiltonian [2], $H_{\boldsymbol{k}} = -2t_1\tau_x \cos(k_x/2)\cos(k_y/2) - t_2(\cos k_x + \cos k_y) + \lambda\tau_z(\sigma_y \sin k_x - \sigma_x \sin k_y) + J\tau_z \boldsymbol{\sigma}\cdot\boldsymbol{n},$ where the first and second terms represent the hopping of electrons, the third term the spin-orbit interaction, and the fourth term the exchange interaction between the Néel vector $\boldsymbol{n}$ and the electron spin $\boldsymbol{\sigma}$. The pseudospin operator $\boldsymbol{\tau}$ is introduced to describe the sublattice degree of freedom. This model has two massless Dirac points at the Brillouin-zone boundary only when $\boldsymbol{n} \parallel \langle 100 \rangle$. Therefore, in this system, the magnetic structure is closely related to the electronic structure.

In this study, we investigate the real-time dynamics of the effective model induced by a dc electric field as a theoretical simplification of an off-resonant terahertz pulse and by a resonant optical pulse. A vector potential of the external field, $\boldsymbol{A}(t)$, is substituted into the Hamiltonian as $H_{\boldsymbol{k}} \mapsto H_{\boldsymbol{k}-\boldsymbol{A}}$. The Schrödinger equation for the electrons and the Landau–Lifshitz–Gilbert equation for the sublattice spins are numerically solved by using the fourth-order Runge–Kutta method. It is found that the sublattice spins show oscillations with the timescale of 0.1–1 ps depending on the polarization of light, which accompanies the change in the energy gap at the Dirac points [see Figure 1]. We will show the detailed results with a focus on the amplitude and polarization dependences, and discuss the possibility of the ultrafast photocontrol of the magnetic and electronic structures in the antiferromagnetic Dirac semimetals.

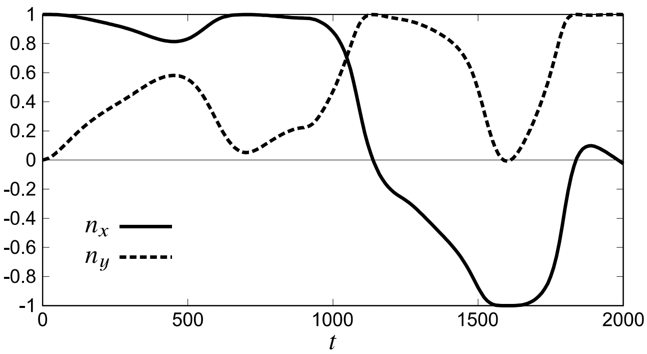

Figure 1: Real-time evolution of the Néel vector $\boldsymbol{n} = (n_x, n_y, n_z)$ under the dc field in the [110] direction. The unit of time is approximately 1 fs.

References:

[1] J. Železný *et al.*, Phys. Rev. Lett. **113**, 157201 (2014); P. Wadley *et al.*, Science **351**, 587 (2016).

[2] L. Šmejkal, J. Železný, J. Sinova, and T. Jungwirth, Phys. Rev. Lett. **118**, 106402 (2017).