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Chirality-Induced Phonon-Spin Conversion at an Interface

Kato Group

Chirality has been an important concept not only in high-energy physics but also in solid state physics for long time. The chirality in materials has attracted much attention after the discovery of chirality-induced spin selectivity (CISS) in DNA and peptides [1]. Indeed, the discovery of CISS has stimulated many theoretical and experimental studies on spin-related phenomena in chiral materials since it may reveal a way of developing spintronic devices without using heavy elements.

Recently, thermal phonon transport in a chiral crystal, a-quartz (SiO_2), induces spin current into an adjacent normal metal [2] as shown schematically in Fig. 1 (a). This observation is quite remarkable since a-quartz is nonmagnetic and includes no heavy elements, which induce spin-orbit interactions. While this CISS phenomenon due to phonon transport is naively explained by angular momentum transfer from chiral motion of nuclei to spins of conduction electrons, its microscopic origin remains unanswered because of the lack of understanding of the microscopic description underlying interfacial phonon-spin conversion

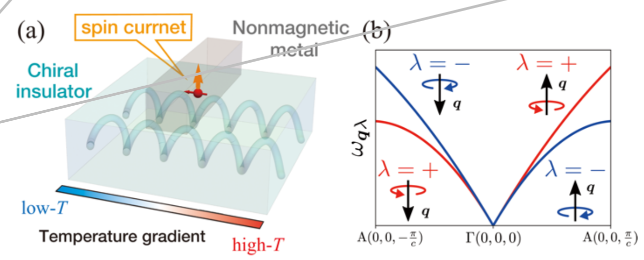

Fig. 1. (a) Schematic setup. Heat current in the chiral insulator generates a spin current in the normal metal through an interface. The generated spin current can be observed by a voltage in the NM induced by the inverse spin Hall effect. (b) Schematic illustration of energy dispersion splitting for chiral phonons. The red and blue lines represent the energy of the right-handed (λ=+) and left-handed (λ=-) chiral phonon modes, respectively.

The key idea to solve this problem is reconsideration on microscopic spin-phonon coupling. Usually, it is derived from energy change of electrons induced by lattice displacement in combination with the spin-orbit interaction. In our work [3], we focused on a previously overlooked mechanism derived from the gyromagnetic effect [4], considering the coupling between local microrotations and electron spins. The gyromagnetic effect has been studied originally as the interconversion phenomenon between spin and macroscopic mechanical rotation. We have now extended it to microscopic rotation, revealing a nontrivial spin-phonon coupling. Starting with a microscopic model for a bilayer system composed of a normal metal and chiral insulator, we derived the effective Hamiltonian describing the interfacial coupling between the electron spins and chiral phonons due to the spin-microrotation coupling. In our study, chirality is characterized by time-reversal symmetry and lack of the parity(mirror) symmetry with respect to spatial inversion. This feature is reflected by splitting of the phonon dispersion $\omega_{q\lambda}$ as schematically shown in Fig. 1(b), where $\boldsymbol{q}$ is the wavenumber and $\lambda = \pm$ is the chirality of phonons. When the phonons propagate along the chiral axis, their energy becomes different ($\omega_{q+} \neq \omega_{q-}$) due to the chirality of the crystal. The phonon dispersion lacks the parity symmetry ($\omega_{q\lambda} \neq \omega_{-q\lambda}$), while it keeps the time-reversal symmetry ($\omega_{q\lambda} = \omega_{-q\bar{\lambda}}$) where $\bar{\lambda} = \mp$ indicates the chirality opposite to λ.

By treating this interfacial coupling perturbatively, we formulated the spin current injected from the chiral insulator into the normal metal. The results suggest that an imbalanced distribution among the chiral phonon modes, e.g., due to a temperature gradient, drives the interfacial spin current into the normal metal. By a simplified calculation assuming the relaxation time approximation, the spin current into the normal metal is obtained as

$$I_s^z \propto \sum_{q\,(q_z>0)} q_z^2 \frac{\partial}{\partial q_z}\left(\omega_{q+}^4 - \omega_{-q+}^4\right)\left(-\frac{\partial_z T}{T}\right)$$

Combining this result with chiral property of phonons described above, we can show that nonzero spin current is generated across the interface only for chiral insulators.

Our findings clearly illustrate the microscopic origin of the spin current generation by chiral phonons without the spin-orbit interaction and may lead to a breakthrough in the development of spintronic devices without heavy elements.

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