Monopole Current and Unconventional Hall Response on Topological Insulator

Jiadong Zang[1,2] and Naoto Nagaosa[1,3]

[1] *Department of Applied Physics, University of Tokyo, Tokyo 113-8656, Japan*

[2] *Department of Physics, Fudan University, Shanghai 200433, China*

[3] *Cross Correlated Materials Research Group (CMRG), ASI, RIKEN, WAKO 351-0198, Japan*

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We study theoretically the charged current above a topological insulator (TI) separated by a ferromagnetic insulating layer. An unconventional Hall response occurs in the conducting layer on top of the TI which approaches to a constant value independent of R for $R \ll \ell$ and decays with $\propto R^{-1}$ for $R \gg \ell$, where R is the separation between TI and conducting layer and ℓ is the screening length. In the comoving frame, it can be interpreted as a monopole current attached to the TI surface. The same mechanism gives the Hall response and deflection of the electron beam injected to the surface of insulating ferromagnet. A realistic estimate of an order of magnitude shows that both effects give reasonably large signal experimentally accessible.

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Topological insulator (TI) is a new state of matter realized in the noninteracting electron systems, i.e., the nontrivial band structure characterized by the "twist" of the Bloch wavefunction in the momentum space[1][2][3][4]. As in the case of quantum Hall system, there is a gap in the bulk states, and the manifestation of the nontrivial topology appears on the surface (edge) of the three (two) dimensional TI[5]. In the case of 3D TI, there appears the helical Dirac fermions on the surface, which is robust against the disorder. This helical metal state is expected to produce the several novel properties such as the topological magneto-electric (TME) effect[5], and an image magnetic monopole when a charge is put above the TI[6]. For these effect to be observed, the time-reversal symmetry breaking is needed, which can be achieved by the ferromagnetic thin layer attached on top of TI, which induces the exchange coupling and the gap to the surface Dirac fermion and its anomalous Hall effect (AHE). Especially, when the Fermi energy lies within the gap, the Hall conductance is predicted to be quantized as $\pm e^2/(2h)$, i.e., half of the conductance unit. When this condition is satisfied, the distribution of the magnetic field outside of the TI is that given by the image magnetic monopole inside the TI. However, in realistic situation, the Fermi energy is rather difficult to control, and lies within the finite density of states of the surface Dirac fermions even with the gap opens by the exchange coupling.

When the TI surface is gapped, and the Fermi surface exactly lies in the gap, the effective electromagnetic response of a 3D TI can be described by θ-term in the Lagrangian[5],

$$\mathcal{L}_{eff} = \frac{\theta}{2\pi}\frac{\alpha}{4\pi}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma} \tag{1}$$

where $F_{\mu\nu}$ is the electromagnetic field strength, and α is the fine structure constant. $\theta = 0$ for conventional insulator, while $\theta = \pm\pi$ for TI. Concerning the chiral anomaly, the sign above is decided by the direction of a magnetic field or magnetization on the TI surface. This

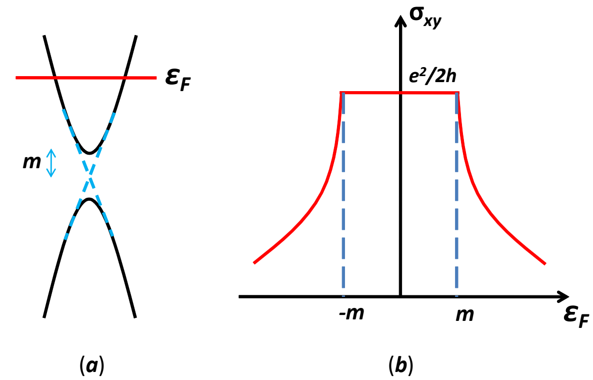

FIG. 1: Sketch of (**a**) the relative positions of Fermi surface ε_F and the magnetic gap m and (**b**) relation between Hall conductance and the Fermi surface. When the Fermi surface lies in the magnetic gap m, the conductance is quantized as half the conductance quanta. However, when the Fermi surface is pushed outside the gap, σ_{xy} decays inversely proportional to ε_F.

nonvanishing θ leads to the topological magneto-electric effect of TI. As a result, when a pure charge is placed on the top of a chirality fixed TI surface, its electric field induces a magnetic field. It's amazing that this magnetic field lines originate from the charge's mirror position with respect to the TI surface. In this sense, we may say that a charge would induce a monopole in the mirror with the help of TI[6]. Without losing the generality, assume the unity dielectric constant and magnetic permeability of the TI. The monopole strength of the induced monopole in SI units is given by $g = \frac{2\alpha\mu_0 c}{(4+\alpha^2)}q = \frac{e^2}{2h}\frac{2\mu_0}{\varepsilon_0(4+\alpha^2)}q$, with α being the fine structure constant.

Phenomenologically TME can be best interpreted as the quantum Hall effect on the TI surface by applying the bulk-edge correspondence. In the presence of a perpendicular magnetic field, quantum Hall effect with half