Theory of orbital magnetoelectric response

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Certain insulators with broken inversion and time-reversal symmetries can exhibit the magnetoelectric (ME) effect, defined as the linear dependence of the magnetization $\mathbf{M}$ (polarization $\mathbf{P}$) on an applied electric (magnetic) field. In the same way that $\mathbf{M}$ is related to bound surface currents, the change in $\mathbf{M}$ under an electric field $\mathbf{E}$ is related to a dissipationless surface Hall effect. The addition or removal of a quantum anomalous Hall layer to the surface leads to a quantum of indeterminacy in the isotropic ($\mathbf{M} \parallel \mathbf{E}$) response. This is analogous to the quantized change in $\mathbf{P}$ associated with changing the number of bound electrons per surface unit cell. Recently, the bulk expression for the orbital part of $\mathbf{M}$ has been derived at $\mathbf{E} = \mathbf{0}$ [1], and in this work [2] we derive the corresponding expression for $\partial\mathbf{M}/\partial\mathbf{E}$ (orbital ME polarizability, or OMP). The resulting expression comprises two types of terms. The Chern-Simons term is reminiscent of the Berry-phase formula for $\mathbf{P}$ [3], and yields a purely isotropic response with a quantum of indeterminacy. The other are more conventional-looking linear-response terms, which contribute to both the isotropic and traceless parts of the OMP tensor. In normal ME insulators both types of terms are present. Surprisingly, in the so-called strong topological insulators the Chern-Simons term has a nonzero value, even though time-reversal symmetry is unbroken in the bulk (it must however be broken at the surface). The absence of bulk inversion and time-reversal symmetries in non-topological ME materials also leads to a spatial-dispersion optical effect known as "gyrotropic birefringence" which is closely related to the ME effect. We show that our expression for the traceless part of the OMP can be recovered by expanding the optical conductivity to first order in the wavevector of light, and then taking the limit $\omega \to 0$.

[1] T. Thonhauser, D. Ceresoli, D. Vanderbilt, and R. Resta, Phys. Rev. Lett. **95** 137205 (2005).

[2] A. Malashevich, I. Souza, S. Coh, and D. Vanderbilt, arxiv:1002.0300.

[3] R. D. King-Smith and D. Vanderbilt, Phys. Rev. B, **47** 1651 (1993).