New Fundamental Magnetic Law Uncovered

A new formula that connects a material’s magnetic permeability to spin dynamics has been derived and tested 84 years after the debut of its electric counterpart.

By **Andrei Sirenko**

If antiferromagnets, altermagnets, and other emerging quantum materials are to be harnessed for spintronic devices, physicists will need to better understand the spin dynamics in these materials. One possible path forward is to exploit the duality between electric and magnetic dynamics expressed by Maxwell’s equations. From this duality, one could naively expect mirror-like similarities in the behavior of electric and magnetic dipoles. However, a profound difference between the quantized lattice electric excitations—such as phonons—and spin excitations—such as paramagnetic and antiferromagnetic spin resonances and magnons—has now been unveiled in terms of their corresponding contributions to the static electric susceptibility and magnetic permeability.

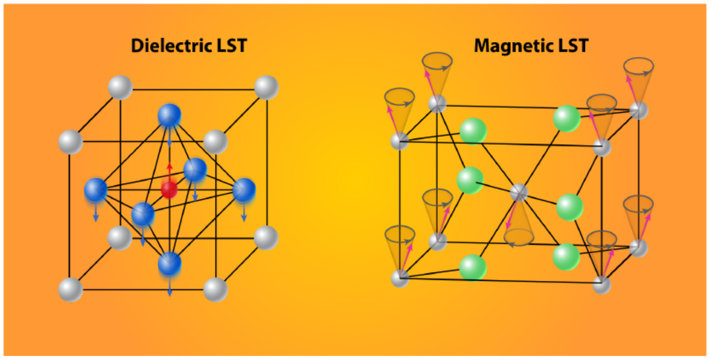

Figure 1: Left: The original Lyddane-Sachs-Teller (LST) relation specifies the dielectric function in terms of the frequencies of lattice vibrations. Right: The new formula for magnetic LST specifies the magnetic permeability in terms of the precession frequencies of magnetic dipoles.
Credit: A. Sirenko/NJIT; APS/C. Cain

Viktor Rindert of Lund University in Sweden and his collaborators have derived and verified a formula that relates a material’s magnetic permeability to the frequencies of magnetic spin resonances [**1**]. Whereas a well-established formula for the dielectric function—the electric equivalent of magnetic permeability—features a quadratic dependence on phonon frequencies, the new magnetic formula features a linear dependence on magnetic frequencies. Just as significant as the formula itself is the way in which it was validated, using a new optical technique that is set to be broadly useful for characterizing spintronic materials.

Identifying relationships between the static and dynamic properties of materials is one of the main aims of condensed-matter physics. In the case of the static dielectric function $\epsilon_{\rm dc}$, the main dynamical contributors are phonons (quantized lattice vibrations) and electronic optical transitions, both of which can be described using a set of oscillators with resonant frequencies. Through their interactions with electrons, phonons determine thermal and electrical conductivity and optical absorption spectra and are responsible for quantum effects, such as conventional superconductivity.

In 1941 Russell Lyddane, Robert Sachs, and Edward Teller published an elegant relationship between $\epsilon_{\rm dc}$ and the longitudinal and transverse optical phonon frequencies $\omega_{\rm LO}$ and $\omega_{\rm TO}$[**2**](Fig. **1**):

$$\epsilon_{\rm dc} = \epsilon_\infty \prod_i^N \frac{\omega_{\rm LO}^2}{\omega_{\rm TO}^2}$$

Known as the Lyddane-Sachs-Teller (LST) relation, this formula appears to this day in textbooks because of its usefulness. It is crucial to describe the behavior not only of the “soft” phonon modes associated with ferroelectric phase transitions but also of a wide class of high-frequency electronic devices.

Rindert and his collaborators derive a different formula for the static magnetic permeability μ_{dc}:

$$\mu_{\mathrm{dc}} = \prod_{i}^{N} \frac{\omega_{\mathrm{LO}}}{\omega_{\mathrm{TO}}}$$

Note that in this magnetic LST relation, the longitudinal and transverse frequencies of the magnetic excitations are raised to the first power rather than squared. Qualitatively, Rindert and his collaborators understood this unexpected result as arising from the difference between spin precession and ionic motion. Confirming that intuition qualitatively required both experiments and theory.

For their experiments the researchers used a sample of the semiconductor gallium nitride, which whey doped with paramagnetic iron to create a magnetic material. To derive the terms on the right-hand side of the magnetic LST, ω_{LO} and ω_{TO}, the researchers measured the spectra of the iron dopants’ paramagnetic optical resonances under a high magnetic field and with a superfine resolution (on the order of 10 kHz for the optical transitions at 125 GHz). By using a technique called Mueller-matrix ellipsometry, they completely characterized the polarization state of light reflected from a sample. The resulting 4 × 4 Mueller matrix facilitated the unambiguous differentiation between magnetic and electric dipoles. To derive the term on left-hand side of the magnetic LST, they measured μ_{dc} with a high-precision superconducting quantum interference device (SQUID).

The second, equally crucial step was the application of Felix Bloch’s 1946 theory that describes spin precession in a magnetic field. Rindert and his collaborators quantified the spin contribution to μ_{dc} and identified the direction of the spin precession for the first time, enabling them to fit the density of the activated magnetic impurities as obtained using optical spectroscopy. Together, the theory, spectroscopy, ellipsometry, and SQUID measurements aligned seamlessly to provide a comprehensive and consistent validation of the researchers’ magnetic LST relation.

Rindert and his collaborators’ study is highly significant for the broader optical community working with antiferromagnetic and altermagnetic materials. Their integration of experiment and theory represents a groundbreaking approach to magneto-optical characterization of ferromagnetic materials with zero net spin that are potentially suitable for gigahertz-frequency applications. What’s more, a broad range of applications of this characterization approach may not require sophisticated high-frequency-resolution techniques such as the Mueller-matrix spectroscopy used to validate the new magnetic LST relation: Many magnetic materials do not require kilohertz-scale spectral resolution to identify the ω_{LO} and ω_{TO} frequencies. Namely, conventional reflectivity and transmission may be sufficient if magnetic dipoles in the material are sufficiently strong. In short, this methodology has great potential for designing and characterizing future spintronic and nanoelectronic devices.

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REFERENCES

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