

Invited Comment

Theory of neutron scattering by electrons in magnetic materials

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Abstract

A theory of neutron scattering by magnetic materials is reviewed with emphasis on the use of electronic multipoles that have universal appeal, because they are amenable to calculation and appear in theories of many other experimental techniques. The conventional theory of magnetic neutron scattering, which dates back to Schwinger (1937 *Phys. Rev.* **51** 544) and Trammell (1953 *Phys. Rev.* **92** 1387), yields an approximation for the scattering amplitude in terms of magnetic dipoles formed with the spin (\mathbf{S}) and orbital angular momentum (\mathbf{L}) of valence electrons. The so-called dipole-approximation has been widely adopted by researchers during the past few decades that has seen neutron scattering develop to its present status as the method of choice for investigations of magnetic structure and excitations. Looking beyond the dipole-approximation, however, reveals a wealth of additional information about electronic degrees of freedom conveniently encapsulated in magnetic multipoles. In this language, the dipole-approximation retains electronic axial dipoles, \mathbf{S} and \mathbf{L} . At the same level of approximation are polar dipoles—called anapoles or toroidal dipoles—allowed in the absence of a centre of inversion symmetry. Anapoles are examples of magneto-electric multipoles, time-odd and parity-odd irreducible tensors, that have come to the fore as signatures of electronic complexity in materials.

Keywords: magnetic neutron scattering, magneto-electric multipoles, YBCO

(Some figures may appear in colour only in the online journal)

Prologue

The interaction between neutrons and electrons was explored in the 1930s, followed by a definitive study in 1953 by Trammell that later was reformulated in a more compact format. Why revisit these calculations after six decades during which time magnetic neutron scattering has become the method of choice for determining motifs of magnetic dipoles and their excitations, e.g., spin-waves? The principal motivation is to complete available calculations by including electronic operators that change sign when space coordinates are inverted, whereas the magnetic dipole is unchanged by inversion.

By way of orientation, consider the amplitude for the magnetic scattering of neutrons by electrons in the limit of

small scattering angles, i.e., a small scattering wavevector k . The scattering amplitude is $\mathbf{Q}_\perp = [\mathbf{k} \times (\mathbf{Q} \times \mathbf{k})]/k^2$, in which an intermediate operator

$$\mathbf{Q} \approx (1/2)(2\mathbf{S} + \mathbf{L}) + i[\mathbf{k} \times \mathbf{D}]/k,$$

can be justified for small k . The first contribution to \mathbf{Q} is the magnetic dipole moment; the magnetic axial vector $\mathbf{Q} \approx (1/2)(2\mathbf{S} + \mathbf{L})$ is likely to be a familiar approximation to all who use the neutron scattering technique to study magnetic materials (an atomic form factor in \mathbf{Q} is approximated by unity for the moment). By contrast, the second contribution $i[\mathbf{k} \times \mathbf{D}]$ with \mathbf{D} both magnetic (time-odd) and polar (parity-odd) is most likely not expected. The dipole \mathbf{D} has no matrix

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