Optical anapoles

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The anapole, a non-radiating charge-current configuration, was recently observed in a variety of artificial materials and nanostructures. We provide a brief overview of this rapidly developing field and discuss implications for spectroscopy, energy materials, electromagnetics, as well as quantum and nonlinear optics.

Toroidal electrodynamics, a new chapter of electromagnetics research is currently attracting considerable and growing attention1–4. It includes the study of toroidal multipoles and anapoles (see Fig. 1). The recent surge of interest in toroidal multipoles is driven by the emerging understanding that alongside the well-known electric and magnetic multipoles they are necessary for a complete characterization of the electromagnetic properties of matter2. Indeed, while electromagnetic fields in free-space can be fully characterized with transverse electric (TE) and transverse magnetic (TM) multipoles5, the characterization of current density requires three multipole series, the electric, magnetic, and toroidal multipoles6,7 (see Fig. 2). The distinctive role of toroidal multipoles is particularly apparent in the optical properties of matter containing large molecules or structural elements of toroidal symmetry and of size comparable to the electromagnetic wavelength. Dynamic toroidal response of metamaterials had been the subject of intense discussions since 20078,9, but the first unambiguous experimental demonstration of dominant toroidal response in matter was recorded in a microwave metamaterial in 20101 (see Fig. 3). Subsequently, dynamic toroidal response has been observed in metallic10–15, plasmonic16–22, and dielectric metamaterials23,24 at frequencies ranging from microwave through to terahertz and up to near-infrared/visible parts of the spectrum (see Fig. 3). The analysis of transmission, reflection12, and polarization phenomena13 in complex molecular systems and metamaterials is incomplete without account of the dynamic toroidal response. Toroidal resonances could play a role in nano-lasers19, sensors25, and data storage devices3,26. We shall also note that static toroidal dipoles, also known as ‘static anapoles’ introduced by Ya. B. Zeldovich in the context of parity violation in nuclear physics27, have been observed in magnetism26 and could be the only allowed electromagnetic form-factor for dark matter candidate particles28.

An electric dipole (a pair of oscillating charges) together with a toroidal dipole (oscillating poloidal current on a torus (see Fig. 1)) can form a non-radiating charge-current configuration.

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The anapole state emerges at a particular frequency of oscillations when the fields radiated by the co-located electric and toroidal dipoles cancel each other through destructive interference. Crucially, electric, and toroidal dipoles have identical radiation patterns (see Fig. 2), thus the net emission of an anapole is zero. The dynamic anapole, a non-radiating energy "reservoir", has inspired a broad search for anapole excitations in a diverse range of structures is a significant achievement in the field of toroidal electrodynamics that illustrates the independent physical nature of electric and toroidal dipoles despite them having identical far-field radiation pattern (see recent discussion of this subject in refs. 42, 43). Indeed, although their far-field emission patterns are identical, the electric and toroidal dipoles correspond to entirely different charge and current distributions (see Figs. 1 and 2).

Furthermore, the oscillating vector potential emitted by electric and toroidal dipoles differs in a way that is irremovable through gauge transforms.

Detection of anapoles
Recent detection of anapole modes in a diverse range of structures is a significant achievement in the field of toroidal electrodynamics that illustrates the independent physical nature of electric and toroidal dipoles despite them having identical far-field radiation pattern (see recent discussion of this subject in refs. 42, 43). Indeed, although their far-field emission patterns are identical, the electric and toroidal dipoles correspond to entirely different charge and current distributions (see Figs. 1 and 2). Furthermore, the oscillating vector potential emitted by electric and toroidal dipoles differs in a way that is irremovable through gauge transforms.

The independent physical significance of toroidal and electric dipoles also manifests itself in relativistic electrodynamics.
Although fields emitted by electric and toroidal dipoles, when in inertial motion, are identical, linear acceleration of oscillating electric and toroidal dipoles changes the polarization properties of the respective radiated fields in a different way: the absolute value of ellipticity of the toroidal dipole radiation becomes greater than that of electric dipole. The difference in ellipticities $\Delta \chi$ diverges along the dipole axis (see Fig. 4). Therefore, an ideal anapole, that is well-balanced to emit no radiation when at rest, will emit light and interact with light, when accelerated.

The effect described above requires extremely high accelerations, and is challenging to observe. However, there is a more accessible way of revealing the difference between the electric and toroidal dipoles. It exploits the difference in coupling of electric and toroidal dipoles to electromagnetic fields in ambient media, and can thus be seen as a form of solvatochromism, a phenomenon of changing the color of a chemical substance depending on the host-solvent. Indeed, the power $P$ emitted by a point-like electric dipole $p$, and a point-like toroidal dipole $T$, oscillating with angular frequency $\omega$, depends on the ambient refractive index $n$ in a different way:\46–48:

$$P_e = \frac{\mu_0 \omega^2 n \cdot |p|^2}{12\pi c},$$

$$P_T = \frac{\mu_0 \omega^2 n^2 \cdot |T|^2}{12\pi c},$$

where $\mu_0$ is the vacuum permeability and $c$ is the speed of light in vacuum. While the power emitted by electric dipole scales as linearly proportional to the refractive index $n$, emission of toroidal dipole scales as $n^3$. Such a difference can be detected by measuring the decay rates of atoms, molecules, or artificial metamaterials, exhibiting toroidal and electric dipole resonances, in ambient environments, e.g. solvents, with different indices of refraction.\46 Similarly, contributions from electric and toroidal dipoles can be distinguished by measuring absorption of artificial metamaterials immersed in liquids with different refractive index.\49

**Future perspective.** The study of anapoles promises some intriguing discoveries. It has been shown that dynamic anapole modes are supported in artificial metamaterials. Could the dynamic anapole be present in organic matter that is often built from molecules with elements of toroidal symmetry such as benzene rings? Indeed, some fullerenes support static anapoles. Moreover, static anapoles have been recently theoretically identified in some cyclic molecules, diatomic molecules, and chiral molecules. Interactions between toroidal currents allegedly break reciprocity, which could have implications for energy and information transfer at the molecular level and for the dynamics of chemical and biochemical processes. As anapoles are energy reservoirs with a long lifetime, they could be of considerable importance as qubits for quantum technologies. High quality anapole-related resonances can be used in enhancing nonlinear electromagnetic properties of materials and in sensor applications. Matter with high density of anapoles could be an exotic energy storage material from which energy bursts could be released by sudden changes in ambient conditions. Spectroscopy of anapoles presents considerable challenges due to weak coupling to free-space electromagnetic waves, as explained above. However, the use of structured light, most notably space-time non-separable pulses with toroidal topology may help, as they are better suited to drive toroidal excitations than transverse pulses. Alternatively, toroidal and electric dipole constituents of an anapole mode could be engaged with electron beam excitations.\60

**Data availability**

Following a period of embargo, the data from this paper will be available from the University of Southampton ePrints research repository: https://doi.org/10.5258/SOTON/D0914.

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