PHYSICS

A new spin on special relativity

Magnetic domain walls have their own speed limit.

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Over a decade ago, weak magnetic fluctuations called spin waves were found to undergo the Doppler effect in magnetic wires (*1*). That experiment demonstrated that spin waves obey a version of Galilean relativity. This relativity is not the kind that we experience, but an emergent instance embedded within the spin waves' own magnetic realm own magnetic realm. On p,. XXX of this issue, Caretta et al. (2) show that domain walls, twists in a material's magnetization, obey not only Galilean relativity but also Einsteinian special relativity. The authors experimentally demonstrate that domain walls possess fundamental velocity limits corresponding not to the speed of light but instead to the limiting speed of high energy spin waves.

The physics that leads to ferromagnetism pushes neighboring spins to be aligned. In 1D magnetic systems magnetic domain walls arise when the magnetization is forced to point in opposite directions at each end of the wire (see the figure). Competition between local alignment physics and the fixed ends causes a smooth transition to occur, like a twist in a ribbon, somewhere in the wire. Structural asymmetries of the atomic lattice cause a preference for the magnetization to align with a particular axis, giving this twist a finite extent, rather than it spanning the entire system. The domain wall thus acts like a compact object embedded in the magnetic structure to which a position, size, and velocity can be ascribed (*3,4*).

Domain walls can be moved back and forth through magnetic wires by a combination of applied magnetic fields and electronic currents. This property has resulted in proposals to use many domain walls in a single wire as a memory device (*5*). Recent progress has led to samples capable of supporting faster domain wall motion than ever before (*6, 7*).

Theorists have predicted (*8, 9*), however, a fundamental speed limit that exists for these domain walls. These predictions rely on approximating the spins as a continuum, rather than a lattice, making the physics more amenable to a classical analysis. The resulting equation of motion for the domain wall is called the sine-Gordon equation, which possesses a similar structure to the equations governing electromagnetic fields.

In classical electromagnetism, the speed of light c is constant across all reference frames. In the equations governing the domain wall, c is replaced by the spin wave speed c_m, which depends on the properties of the magnetic material. This replacement suggests that c_m is constant across all reference frames to which the domain wall equations apply. Unlike the theory of electromagnetism, which seems to hold throughout the known universe, this sine-Gordon equation only applies to observers who are part of the magnetic wire. Two scientists, moving at different speeds in a lab, would not expect c_m to appear constant. However, to two domain walls in the wire, c_m would be constant, even if the walls were moving at different speeds.

The constancy of c_m leads to consequences similar to what Einstein predicted in special relativity (*10*). A moving domain wall should appear contracted in length to a stationary observer. The moving domain wall should appear to experience the passage of time more slowly and the frequency of spin waves will appear to shift between different reference frames. Finally, no matter how much force is applied to a domain wall, it can never go faster than c_m. These properties are collectively described as Lorentz invariance, a property possessed by both the sine-Gordon equation (with respect to c_m) and the equations of special relativity (with respect to the speed of light c).

To experimentally demonstrate the Lorentz invariance of domain walls, Caretta et al. perform a series of trials moving domain walls while varying the electric current and external magnetic field. Domain walls in the material act like sailboats in a "wind" of magnetic field. In the absence of electronic current, the domain wall's "sail" lies parallel to the wind, so that it experiences no driving force. Turning up the current causes the sail to open, catching the magnetic field's wind and causing the domain wall to move. As the current increases, the sail becomes nearly perpendicular to the wind, and so the velocity should saturate as the sail simply cannot open any further. But the Lorentz invariance of the sine-Gordon equation leads to a surprising, second prediction. Holding the sail constant while increasing the wind also leads to velocity saturation, even in the absence of dissipative mechanisms like friction or viscosity. An observation of this unintuitive result would constitute evidence of the relativistic limit.

Caretta et al. indeed find this relativistic saturation in their experiment. As the authors ramp up field and current, the domain wall speed asymptotically approaches the theoretically predicted c_m value of about 5 km/s, for the magnetic material. To verify that this saturation is relativistic, the authors perform lattice-based simulations of the experiment. After confirming that the simulated current-field-velocity relations matched the measurements, the authors extract the lengths of the domain walls during their simulated flights. The authors find that simulated domain walls moving at velocity v shrink in size by a factor of $/1 - v^2/c_m^2$, exactly as expected from relativistic length contraction.

One other consequence of special relativity is the lack of a preferred reference frame as demonstrated by Michelson and Morley (11). However, weak couplings that exist between the spins and the rest of the atomic lattice can allow energy and momentum to leak out of the Lorentz-invariant theory. These leaks manifest as viscous drag on the domain wall, leading to the somewhat obvious preferred reference frame of the laboratory where friction vanishes. This weak preference for the laboratory reference frame is a reminder that, despite the beautiful physics emergent in many-body systems, it remains just that -- emergent. The authors' verification of emergent Lorentz invariance in domain wall systems nevertheless places important constraints on what can be achieved in magnetic technology, and challenges those in the field to find experimental evidence of other relativistic magnetic phenomena.

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