PHYSICS

Understanding the call of the monopole

Mysterious magnetic noise of elusive particles is finally understood

By **Felix Flicker**

Noise is often thought of as merely a hindrance to detecting a signal, but it frequently contains vital clues to otherwise hidden behavior. Recently, noise has been used to hunt for elusive particles called emergent magnetic monopoles, which are predicted to exist within crystals called spin ices (*1*). Monopoles would feature a magnetic charge that resembles the north pole of a magnet moving independently of the south pole. In 2019, the first noise measurements on monopole dynamics revealed distinctive spontaneous noise in the magnetization of spin ices (*2*). However, the noise differed from the simplest expectations for magnetization coming from moving magnetic particles. On page 1218 of this issue, Hallén *et al.* (*3*) propose that natural constraints in a spin ice restrict monopole motions to a lattice (within the spin ice crystal) that bears a fractional number of dimensions (known as a fractal). Understanding the nature of monopoles in spin ice might have important practical uses, in much the same way that understanding the nature of electrons facilitated modern electronics.

The theory of monopoles in spin ices is elegant in its simplicity. Imagine several bar magnets aligned end to end and pointed in the same direction. Flipping a single magnet gives a double north pole next to a double south pole. Flipping a neighboring magnet distances the double-north from the double-south. Subsequent magnet flips can move the double-north and double-south like independent particles. In a spin ice, this situation is believed to come about naturally, in three dimensions, on the atomic scale. However, Hallén *et al.* explain that not all flips are equal. Using a detailed model of individual atomic environments (*4*), the authors show that the possible future moves of a monopole are constrained both by where the monopoles are situated in the spin ice and where they have been. Separating double north and double south in the line of bar magnets leaves a string of flipped magnets connecting them. Similarly, "Dirac strings" weave through the spin ice. In this case, they constrain the movement of each monopole. The result is a branching tree of possibilities that grows as possible futures split and merge dynamically. The tree has the notable property that it looks the same at all scales. Furthermore, the appearance of a fractal within an ordered crystal is unprecedented.

One role monopoles could play is in the emerging field of spintronics, an alternative to electronics that uses particles' magnetic fields (spins) rather than their electric charges. Spintronic devices offer major efficiency gains and a possible route forward now that the 50-year period of exponential growth governed by Moore's law is ending. Spintronic memories are already commercially available. However, monopoles could replace many electronic devices with magnetic equivalents, in which the magnetic fields of particles are leveraged. The necessary cryogenic temperatures for such "magnetronics" need not be a hindrance in the age of cloud computing. For this to occur, however, the nature of the emergent monopoles and their dynamics must be better understood. This is where noise can help.

"Using noise to understand the hidden world of particles has an ancient precedent."

Using noise to understand the hidden world of particles has an ancient precedent. Roman poet Lucretius saw evidence for the existence of atoms in the dancing patterns of dust in air (*5*). In 1905, Albert Einstein put this on a quantitative footing (*6*). He explained that the Brownian motion of pollen grains in water comes from the jostling of individual water molecules. The pollen's velocity changes randomly from moment to moment, producing a "white noise" of velocity fluctuations; in analogy to white light, any frequency is equally likely to be found. The fluctuations in the position can then be calculated by integrating over time. The result is "red noise" that decreases as the square of the frequency (analogously, removing high frequencies from white light leaves red light). Low-frequency changes in velocity move the pollen grain more than high-frequency changes because they push for longer in one direction.

The study of noise in spin ices began in 2018 when numerical simulations predicted that the noise would instead decrease as the frequency raised to a power between one and two, varying with temperature (*7*). This is called pink noise, lying between red and white. Pink noise is ubiquitous—appearing, for example, in the tide times of the Nile, heartbeat rhythms, scene lengths in films, and financial markets. Although white and red noise are well understood, no general theory of pink noise exists, and its origin and ubiquity remain major unsolved problems in physics.

Hallén *et al.* explain the origin of pink noise in the magnetization dynamics of spin ices as coming from the constrained motion of emergent magnetic monopoles. This unification of theory and experiment parallels the microscopic understanding that underpins the development of modern electronics. Yet much remains to be understood. Noise is the result of the collective motion of many monopoles. A pressing question is how to observe a single monopole. This could in principle be achieved with sufficient advances in low-temperature, atomic-scale magnetic field measurements. The development of electronic devices required a precise understanding of materials' conductive properties over a range of temperatures and driving frequencies. Practical magnetronics would require a similar understanding across the growing range of known spin ice materials. The branching possibilities understood by Hallén *et al.* also suggest an intriguing possibility of spin ices as memory storage devices. Pink noise implies that monopoles have a memory of their past, but the precise form of this memory and its relation to Dirac strings remains to be elucidated. ■

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