Simulation of magnetic monopole motion in spin ice with magnetized surface

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Spin ices have the unusual ability to develop magnetic monopoles following a mechanism similar to the formation of ions in water ice. The behavior of these exotic objects and their effect on the properties of spin ices is an ongoing area of study. We propose a simulation-based analysis of monopole dynamics in spin ice with a magnetized surface. We claim it can be used to understand how monopole *motion* alone can affect the properties of spin ice.

In water ice, oxygen atoms bond to exactly four hydrogen atoms. Two of these bonds are strong covalent bond, while the other two are weaker hydrogen bonds [1]. In other words, each oxygen atom is surrounded by two inward-pointing and two outward-pointing electric dipoles. Excitations which break this structure are the well known H_3O^+ and OH^- ions. Interestingly, *magnetic* materials such as $Dy_2Ti_2O_7$ and $Ho_2Ti_2O_7$ obey similar rules. Only this time, electric dipoles are replaced by spin magnetic dipoles, and excitations are magnetic monopoles. Monopoles form by pairs when individual spins flip, and can then wander throughout the material by flipping consecutive spins. This motion does not produce isolated monopoles, but rather north-south pairs connected by long string-like magnets known as Dirac strings[2].

These oddities and their consequences on the properties of spin ice are a fascinating subject. Most notably, spin ice dynamics manifest an emergent electromagnetic field theory. This property gives us an alternative way to study emergence of field theories in nature, both experimentally and theoretically. Even better, it's possible to engineer artificial spin ice using carefully placed nano-magnets [3]. The resulting system can be tuned at will [4], allowing detailed experimental study of the field theory, as well as its emergence and applications. For example, controlled experiments with artificial spin ice may lead to understand why isolated magnetic monopoles are not observed in nature. On the other side, artificial spin ice can also be used to process and transport spin states, which can be applied to quantum computing [5]. However, we don't need to exhaustively study spin ice properties right away by repeating experiments: classical computers can help us. In that vein, we propose a numerical study of monopoles in spin ice.

The model that we wish to study consists of a spin ice lattice with an induced surface magnetization. By the mechanism previously explained, spin alignment at the surface creates magnetic monopoles in the bulk of the lattice. Given a large magnetization, we can approximate that all monopoles form at the surface. A constant magnetization thus leads to a constant number of monopoles, and to all of them having the same charge. This result allows for an analysis of magnetic monopole dynamics in the absence of creation and destruction of monopole pairs. It means we can quantify the effect of monopole motion alone on spin ice properties.

The first step of our study will be to work out a quantitative description of both the model and the approximation described earlier. We will go as far as to solve the 1-dimensional model if it turns out to be possible. We will then perform a Metropolis simulation of an n-dimensional system at temperature T to image the motion of monopoles and strings. This process will be repeated at multiple different values of T and n to search for qualitative differences in the dynamics. Finally, we will quantify correlation between monopoles as a function of T and n by computing the dynamical structure factor.

In short, magnetic monopole excitations manifest in spin ice following a remarkably simple mechanism, yet they have dramatic consequences, both in theory and in application, on the physical world. Recently, there has been a lot of work on the quantum equivalent of spin ices: quantum spin liquids. Quantum spin liquid has been proposed as a model of high-temperature superconductivity [6]. Perhaps our simple numerical study can be a brick in the tower leading to better understanding of that phenomenon.

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