Spin Textures in Magnetic Multilayers

The purpose of my research this semester is to study solitons in ferromagnetic materials, metals in which unpaired electrons line up in the same direction, creating a magnetic field. A soliton is a wave that propagates through a field while maintaining its shape and speed - think of the way a tsunami travels across water. In magnetic materials, solitons can be thought of as bundles of knotted field lines, creating structures that move through the metal the way a particle would. Important examples of this phenomenon are magnetic Skyrmions, a subgroup of solutions in which the magnetic moments of the atoms in the material align in a vortex-like shape, and then remain in this configuration. Patterns like these are also called spin textures, or patterns in the magnetization vectors at a particular point in the material. These patterns are produced by competing in magnetic interactions that each influence the direction of the spins, creating a stable arrangement that can move through the material while maintaining its structure. Specifically, my research will focus on Hopfions, which can be roughly thought of as 3D Skyrmions. They are stable spin texture with a finite mass but are distinguished from Skyrmions by their topology. The classic Hopfion is a donut like shape made of aligned magnetization vectors. Topologically, this is described by the Hopf charge, the linking number of two 'loops' in 3D real space that contain spins pointing in the same direction - if you imagine two interlocking donuts, these have a linking number of two. Apart from this research providing an opportunity to develop a more complete understanding of these phenomena, these spin textures also have potential technological applications that can become realistic through further study.

The Hellman lab and their collaborators were recently the first to experimentally confirm the existence of stable Hopfions in chiral magnets. This was achieved by first creating a Target Skyrmion (Tsk) and then using the magnetic properties of the material to deform it into a Skyrmion. TSks are extended spin textures defined by the fact that their magnetization vector is rotated more than pi times - essentially, they differ from Skyrmions in the 'vortex shape' of their spin texture. The magnets used host Tsks and Hopfions are multilayers of magnetic materials, also called stacks. Specifically, the stacks used in the discovery of Hopfions consist of 30 Ir/Co/Pt tri-layers, each at most a few nanometers thick. These stacks have two properties which allow them to host and stabilize spin textures: first, the interfaces between the different materials allow for the Dzyaloshinskii–Moriya interaction, an exchange interaction that causes the magnetic moments of the atoms to change their alignments, rather than simply lie in the plane. This allows for the spin textures to form in the material. Second, the Co layers increase in thickness towards the center of the stack, which increases the perpendicular magnetic anisotropy (PMA) towards the top and bottom, while decreasing it towards the center. PMA is an effect which essentially forces the spins to align out of the plane, rather than their original preferred direction. This both stabilizes the spin texture in the center of the stack, pinning it in place, and allows TSks to be transformed into Hopfions. By adjusting the perpendicular magnetic anisotropy at their top and bottom faces, the magnetization at these points begins to match the magnetization at the center of the TSk and making a Hopfion more energetically favorable. Thus, we can tune the PMA of a TSk in order to transform it into a Hopfion, with the Target Skyrmion acting as a precursor to our final goal, creating a Hopfion.

Both Skyrmions and Hopfions have various applications in the field of spin transport electronics (spintronics) due to their stability and high mobility, which means they can be moved through magnetic materials with low power and high speed. Spintronics exploits the spin of electrons to store information, with the advantage of spin being that it can be read in common materials, such as aluminum, rather than only in semiconductors, like charge. This is also more energy efficient than traditional electronics since it takes less energy to change a particle's spin than it does to maintain a current, creating the possibility of future low-energy and high-speed spintronics devices. The energy barrier to changing a Hopfion's topology means they are stable at room temperature and zero field, which makes them an especially attractive candidate for information storage in future low-energy and high-speed spintronics devices. Skyrmions and Hopfions have both been proposed as a method to store information in magnetic fields due to the low energy cost of manipulating them using a spin polarized current. One proposed example of such memory are racetrack devices, which would use spin polarized currents to access information stored in magnetic fields. Such a device would be able to access information much faster, and with lower energy use, than current methods. As the world's need for computing power increases, the need for better storage options will only grow, making spintronics a promising avenue for future research. An improved understanding of these spin textures and how they behave under a current will be crucial to realizing these possibilities.

The goal of my proposed project is to first grow the Ir/Co/Pt films that are used to host Hopfions, and then observe their current-driven dynamics of the Hopfions in these films at the Lawrence Berkeley National Laboratory. These films are difficult to engineer due to the nanometer level accuracy needed; but the Hellman lab is well equipped to synthesize them. This is done using the lab's magnetron sputtering system, a coating process that involves a gaseous plasma which is confined to a space containing the target material. The target is then eroded by the ions within the plasma, and the target atoms travel through the vacuum to deposit onto a substrate, forming a thin film. We will then be measuring the magnetization of the films using a superconducting quantum interference device, or SQUID, which is a very sensitive magnetometer used to measure weak magnetic fields. This work is leading up to microscopy experiments at the Lawrence Berkeley Laboratory, which is where we will be able to observe the Hopfions in the thin films we've grown. Numerical simulations have predicted a large number of dynamics of magnetic Hopfions under an applied current, which are thought to vary based on how the current is controlled. The main ways such currents are constrained are spin transfer torques, wherein a spin polarized current provides torque to a magnet, and spin Hall torques, which split spin polarized currents perpendicular to the current direction. These two different forms of controlled current are expected to move Hopfions through the material in different ways. These theoretical results will be tested using two separate methods: performing mangetotransport measurements and soft magnetic x-ray imaging. We do not expect to observe any transverse motion to the current, as Hopfions are predicted to not exhibit the Skyrmion Hall effect, which causes spin textures' paths to skew to the side. This is an important prediction for potential spintronics applications, as transverse motion would be unwanted in devices like the racetrack memory. Thus, this research would be the first experimental observations of Hopfions under an applied current, through which will be able to gain a deeper understanding of Hopfions' properties and investigate their potential technological benefit in spintronics devices, Student signature: _________________________ Date: ___________

Faculty sponsor signature: _________________________ Date: ___________