Spin Vortices: from Fundamental Physics to Biomedical Applications

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The magnetic ground state of magnetically soft thin film ferromagnets in confined geometries (on the micrometer scale) consists of a curling spin configuration, known as a magnetic vortex state. The vortex is characterized by an in-plane continuous swirling closure spin structure with a core region (typically ~10 nm in diameter) where the spins tilt out of the plane, Fig. 1b, [1, 2]. The vortex state is stable because it generates minimal stray magnetic fields, with the exception of the core area, which forms to satisfy exchange energy considerations. The vortex state can be described in terms of two quantities: a core polarization that defines whether the out-of plane component of the magnetization points up or down, and a chirality that defines the in-plane curling direction (clockwise or counter-clockwise) of the spins. The characteristic reversal mechanism is via nucleation, displacement and annihilation of the vortex [3, 4]. Previous experiments examining the dynamics of the vortex core under the influence of pulsed fields [5] have detected a translational or gyrotropic eigenmode [6] consisting of sub-GHz frequency spiral-like motion of the vortex core about its equilibrium position. The sense of the core rotation is uncorrelated with the vortex chirality and that it is determined solely by the core polarization. Further, it was shown that the magnetic vortex core can be reversed using *rf* magnetic fields of very small amplitude [7], whereas up to several kOe field is required to switch the core with static field [8]. The other higher frequency (5-10 GHz) excitations [9, 10] can be understood (within some approximation) as the usual spin waves in restricted geometries [11]. Magnetic vortices in confined ferromagnets is therefore an important research topic of broad interest due its relevance to the fundamental advancement of our understanding of nanomagnetic systems. Various applications based on magnetic vortex concept include Magnetic Random Access Memories [12], spin oscillators [13, 14], and magnetic field sensors [16, 17].

Furthermore, we have recently demonstrated that the magnetic vortex microdisks (Fig. 1a) can be successfully used as multifunctional magnetic carriers for biomedicine [17]. In particular, we will report on successful interfacing of ferromagnetic nanomaterials with a spin vortex ground state and biomaterials (antibody, whole cell). Namely, the gold-coated lithographically defined microdisks with an Fe-Ni magnetic core were biofunctionalized with anti-human-IL13a2R antibody for specifically targeting human glioblastoma cells. When an alternating magnetic field is applied the vortices shift, leading to the microdisks oscillation that causes a mechanical force to be transmitted to the cell. Cytotoxicity assays, along with optical and atomic force microscopy studies, show that the spin vortex-mediated stimulus creates two dramatic effects: (a) membrane disturbance and compromising, and (b) cellular signal transduction and amplification, leading to robust DNA fragmentation and, finally, programmed cell death [18]. The experiments reveals that by employing biofunctionalized magnetic vortex microdisks the magnetic fields of low frequency of a few tens of Hz and of small amplitude of < 100 Oe applied during only 10 minutes was sufficient to achieve ~90% cancer cells destruction. For comparison, magnetic fields of few hundreds Oe, running at ~ hundreds kHz are typically needed to achieve another type of cytotoxicity, i.e. hyperthermia treatments using superparamagnetic particles. In other words, an external power supplied to the cell cultures in our experiments is ~100,000s times smaller than that applied to magnetic particles that are presently used in hyperthermia applications.

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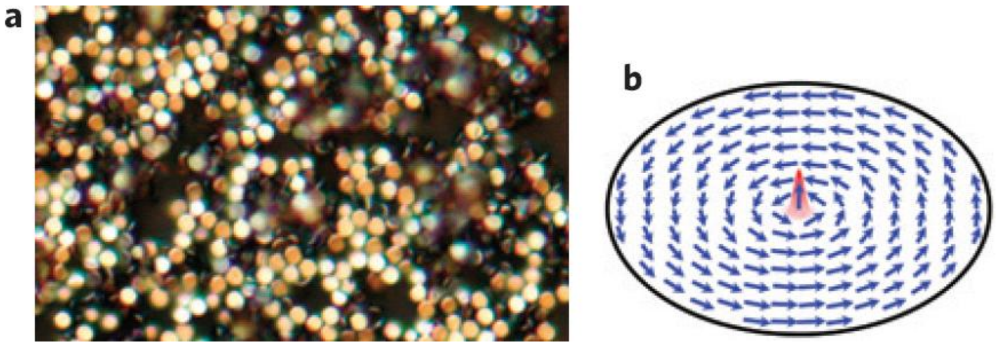

Fig. 1: (*a*) Optical microscope image of the dried suspension of 50-nm-thick, ~1 μm diameter Fe-Ni disks coated with a 5 nm of gold on each side.
(*b*) Micromagnetic model of magnetic-vortex spin distribution.