Theory of magnetic field-stabilized compact skyrmions in thin film ferromagnets

Anne Bernand-Mantel[1, 2, *], Anaïs Fondet[1, 2], Cyrill B. Muratov[3,4], Theresa M. Simon[5], and Valery Slastikov [6]

[1]*Université de Toulouse, Laboratoire de Physique et Chimie des Nano-Objets, UMR 5215 INSA, CNRS, UPS, 135 Avenue de Rangueil, F-31077 Toulouse Cedex 4, France*

[4]*Department of Mathematical Sciences, New Jersey Institute of Technology, Newark, NJ 07102, USA*

[3]*Departimento di Matematica, Universitá di Pisa, L. Bruno Pontecorvo, 5, 56127 Pisa, Italy*

[5]*Institut für Analysis und Numerik, Westfälische Wilhelms-Universität Münster, Einsteinstr. 62, 48149 Münster, Germany*

[6]*School of Mathematics, University of Bristol, Bristol BS8 1TW, United Kingdom*

[2]*Centre d'Elaboration de Matériaux et d'Etudes Structurales, CEMES-CNRS, 29 rue Jeanne Marvig, 31055 Toulouse, France*

**anne.bernand-mantel@cnrs.fr*

Compact magnetic skyrmions are potential bit-encoding states for spintronic memory and logic applications that have been the subject of a rapidly growing number of studies in recent years. Nevertheless, despite numerous attempts, a satisfactory theoretical description of these objects is still lacking today due to the highly non-trivial character of the magnetostatic interaction that plays a major role in determining the nature of magnetization patterns in ferromagnetic materials. The orthodox theory of skyrmions in ultrathin ferromagnetic layers with interfacial DMI relies on a model that accounts for the dipolar interaction through an effective anisotropy term, neglecting long-range effects. At the same time, in single ferromagnetic layers with interfacial DMI, large chiral skyrmions, also called skyrmionic bubbles have been observed, suggesting a non-trivial interplay between DMI and long-range dipolar effects [1]. We will present our work where we used rigorous mathematical analysis to develop a skyrmion theory that takes into account the full dipolar energy in the thin film regime and provides analytical formulas for compact skyrmion radius, rotation angle and energy [2]. Our theory reveals the existence of a new regime at low DMI were skyrmions are stabilized by a combination of non-local dipolar interaction and a magnetic field applied parallel to their core . This predictions are confirmed by our numerical simulations[3]. Finally, we will discuss the theory of skyrmion lifetime in a continuum field theory where we interpret skyrmion collapse events as capture by an absorber at microscale. This yields to an explicit Arrhenius collapse rate for skyrmions with both the barrier height and the prefactor as functions of all the material parameters [4]. Or work provides a guide in material system design in view of optimizing the skyrmion lifetime for applications.

References

[1] Anne Bernand-Mantel, Lorenzo Camosi, Alexis Wartelle, et al. The skyrmion-bubble transition in a ferromagnetic thin film. *SciPost Physics* 4, 027 (2018).

[2] Anne Bernand-Mantel, Cyrill B. Muratov, and Thilo M. Simon. Unraveling the role of dipolar versus Dzyaloshinskii-Moriya interactions in stabilizing compact magnetic skyrmions. *Physical Review B* 101, 045416 (2020).

[3] Anne Bernand-Mantel, Sarah Barnova, Anaïs Fondet, Cyrill B. Muratov, and Theresa M. Simon. Theory of magnetic field-stabilized compact skyrmions in thin film ferromagnets. *arXiv:2306.01413* (2023).

[4] Anne Bernand-Mantel, Cyrill B. Muratov, and Valeriy V. Slastikov. A micromagnetic theory of skyrmion lifetime in ultrathin ferromagnetic films. *Proceedings of the National Academy of Sciences* 119, e2122237119 (2022).

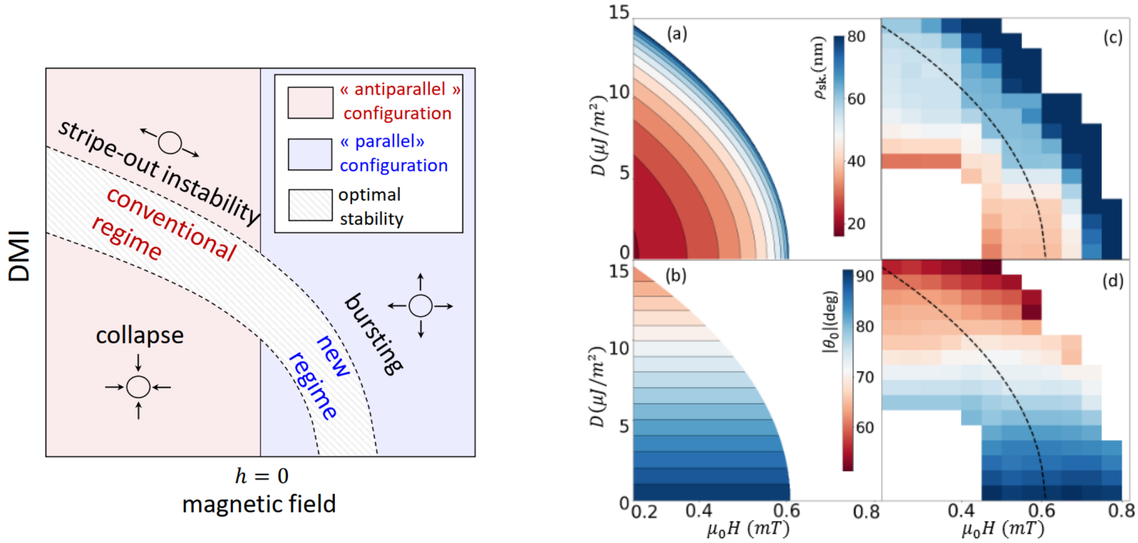

Figure 1: Left side: Schematic representation of the skyrmion phase diagram as a function of DMI and applied magnetic field where positive field is applied in the direction along with the magnetization in the skyrmion core (parallel configuration). We represent 3 types of skyrmion instabilities, stripe out, collapse and bursting as well as the optimal skyrmion stability zone.The new regime of field stabilized skyrmions is indicated. Right side: Analytical predictions of the skyrmion characteristics in the low DMI regime for $d = 5$ nm, $A = 20$ pJ/m, $M_s = 10^5$ A/m, and $K_u = 6346$ J/m^3 corresponding to $Q = 1.01$: (a) Skyrmion radius r_{sky} and (b) skyrmion rotation angle. (c) skyrmion radius and (d) skyrmion rotation angle from MuMax3 simulations on a 2048×2048 nm^2 square box with mesh size $2 \times 2 \times 5$ nm. The dashed line is the line of zero bursting barrier.