Author's Accepted Manuscript

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PII: S0304-8853(16)32459-3
DOI: http://dx.doi.org/10.1016/j.jmmm.2016.10.021
Reference: MAGMA61934

To appear in: *Journal of Magnetism and Magnetic Materials*

Received date: 16 March 2016
Revised date: 21 September 2016
Accepted date: 3 October 2016

Topological strength of magnetic skyrmions

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(Dated: October 6, 2016)

This work deals with magnetic structures that attain integer and half-integer skyrmion numbers. We model and solve the problem analytically, and show how the solutions appear in materials that engender distinct, very specific physical properties, and use them to describe their topological features. In particular, we found a way to model skyrmion with a large transition region correlated with the presence of a two-peak skyrmion number density. Moreover, we run into the issue concerning the topological strength of a vortex-like structure and suggest an experimental realization, important to decide how to modify and measure the topological strength of the magnetic structure.

PACS numbers: 75.70.Kw, 11.10.Lm

I. INTRODUCTION

Topological structures play important role in nonlinear science and may come out as kinks, domain walls, vortices, strings, monopoles, skyrmions and other localized solutions [1–3]. They are static solutions that appear in different spatial dimensions, and in this work we study planar systems, focusing attention on magnetic domains [2] that behave as magnetic spin textures of the vortex or skyrmion type. Such magnetic excitations are of current interest, and have been investigated in a diversity of contexts, in particular in the recent works [4–26], where fabrication and tailoring of skyrmions and skyrmion lattices are important steps toward applications at the nanometric scale, where such spin textures are conceived.

Since the magnetic structures that we study are marked by topological features that describe their skyrmion numbers, we concentrate on issues related to the topology and stability that the localized structures may engender. This is a topic of current interest and we follow the lines of [16–20], which deals with the possibility to control, enhance and measure the strength the topology induces into the solutions. To do this, we follow the recent work [25], in which we have studied vortex and skyrmion properties starting from an exactly solvable model described by a scalar field in two spatial dimensions, as introduced in [27].

We focus attention on the recent investigations [17, 18, 20], where the authors study skyrmions and discuss the measurement [17], and splitting and enhancement [18, 20] of such topological structures. In particular, in [17] the authors construct interesting experimental samples, with a vortex on top of a magnetic material, with the magnetic material having two distinct configurations, one with the magnetic spins pointing upward in the out-of plane direction, and the other with the spins pointing downward. They then apply external in-plane magnetic field, which they control and vary, and show that as the external field increases, one of the skyrmions is destroyed before the other one, indicating the strength the topology plays in the magnetic structures. However, we think that the skyrmions created in [17] are in fact vortices of a specific magnetic material (they used Co circular disk) which sit on top of another material (they used Ni film, grown epitaxially on a Cu(001) substrate) with the Ni spins pointing up and down in the out-of-plane direction, and the effect measured shows how the up and down out-of-plane magnetic contributions of the Ni film change the topological strength of the vortex structure which sits on top of it.

In refs. [18, 20] the authors investigate several issues, among them the two-peak appearance in the topological charge density, which is correlated with the presence of a large *transition region*, representing the *internal structure* of the topological skyrmion. This is another issue that we study in this work, with the investigation of a model which appeared before in [27]. The motivation here is that in the one-dimensional case studied in [27], one found a domain wall similar to the magnetic domain wall that appeared experimentally in $Fe_{20}Ni_{80}$ thin film, in a constrained geometry [28]. As we are going to show, the model can be used to map skyrmion with unit skyrmion number, but with the number density having a two-peak formation, correlated with the presence of a large transition region, the internal structure of the magnetic solution. In the current work, the effect is related to the fractional self-interactions that describe the model, and in Ref. [20] it is supposed to appear in consequence of the Rashba spin-orbit coupling. We recall that the Rashba spin-orbit coupling has been studied in several works, in particular in the experimental and theoretical contexts in Refs. [29–33].

With these motivations in mind, in the current work we describe how to construct theoretically, structures having skyrmion number 1, 1/2, and 0, and show that they all crucially depend on specific physical properties of the material under investigation, so they have to be generated by specific materials, each one with its specific features. This leads us to suggest that the presence of a magnetic vortex on top of an out-of-plane aligned spin arrangement of another magnetic material is still a vortex, with skyrmion number 1/2. It may be a hybrid structure, and to describe our point of view, we organize the work as follows. In the next section we introduce the general framework and briefly review the construction of skyrmions with topological numbers 1 and 1/2, and then study a