Frontiers in Physics

TYPE Editorial
PUBLISHED 23 August 2023
DOI 10.3389/fphy.2023.1275990

OPEN ACCESS

EDITED AND REVIEWED BY
Matthias Eschrig,
University of Greifswald, Germany

*CORRESPONDENCE
Pavel F. Bessarab,
✉ pavel.bessarab@lnu.se

RECEIVED 11 August 2023
ACCEPTED 15 August 2023
PUBLISHED 23 August 2023

CITATION
Uzdin VM, Thonig D, Göbel B and Bessarab PF (2023), Editorial: Nucleation and stability of exotic solitons in condensed matter.
Front. Phys. 11:1275990.
doi: 10.3389/fphy.2023.1275990

Editorial: Nucleation and stability of exotic solitons in condensed matter

Valery M. Uzdin[1], Danny Thonig[2,3], Börge Göbel[4] and Pavel F. Bessarab[5,6]*

[1]Faculty of Physics, ITMO University, St. Petersburg, Russia, [2]School of Science and Technology, Örebro University, Örebro, Sweden, [3]Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden, [4]Institute of Physics, Martin Luther University Halle-Wittenberg, Halle, Germany, [5]Department of Physics and Electrical Engineering, Linnaeus University, Kalmar, Sweden, [6]Science Institute, University of Iceland, Reykjavík, Iceland

KEYWORDS

soliton, condensed matter physics, skyrmion, thermal stability, magnetic material

Editorial on the Research Topic
Nucleation and stability of exotic solitons in condensed matter

Topological solitons in condensed matter are of particular interest for fundamental theory due to a deep connection between topology and physics manifested in these systems. At the same time, they are praised as the basis for new technologies of data storage, information processing, machine learning and neuromorphic computing. The most well-studied magnetic solitons are quasi-two-dimensional skyrmions and bubble domains. However, in recent years, attention has shifted to other two-dimensional and even three-dimensional localized topological structures appearing not only in magnetic materials, but also in liquid crystals, ferroelectrics and multiferroics, which expands our knowledge about topological effects in physics and possible scope of topological soliton applications [1].

Although skyrmions and related objects owe their stability to topology, the topological protection is not strict in real systems due to discrete nature of condensed matter, e.g., magnetic moments localized on atomic lattices. Instead, topological solitons can be nucleated and annihilated by overcoming finite energy barriers. Such over-the-barrier transitions can be induced spontaneously by thermal fluctuations leading to a finite lifetime of the states. Successful implementation of topological solitons in technology requires their lifetime to be sufficiently long, many orders of magnitude longer than characteristic times of the microscopic dynamics. This hierarchy of the timescales makes it challenging to study the thermal stability of the solitons. Consistently with the Néel-Brown theory of thermally activated magnetization reversal [2, 3], experimental observations [4] and numerical simulations [5] of magnetic skyrmions identified Arrhenius dependency of their nucleation/annihilation rates k on temperature T:

$$k = k_0 e^{-\Delta E/k_B T}. \tag{1}$$

However, both the energy barrier ΔE and, remarkably, the pre-exponential factor k_0 which is often taken to be a phenomenological constant, turned out to be highly sensitive to various control parameters such as an external magnetic field [4]. The physics of the thermal stability of magnetic skyrmions was revealed using a statistical approach based on the rate theory for magnetic degrees of freedom [6–9]. Calculations of minimum energy paths

(MEPs) connecting the skyrmion state with topologically trivial background state have uncovered skyrmion collapse mechanisms [10–12], some of which were confirmed experimentally [13]. The rate theory has made it possible to identify, in a definite way, both the energy barrier and the Arrhenius pre-exponential factor. In particular, the unexpected variations of the pre-exponential factor were explained by large entropy difference between the skyrmion state and the transition state–the bottleneck for the skyrmion collapse [11, 14–16]. Overall, recent developments of theoretical and computational methods for the rate theory [17–20] have made it possible to establish a coherent picture about thermal stability of magnetic skyrmions. At the same time, the theoretical framework is quite general and can be applied to solitons beyond magnetic skyrmions.

Two-dimensional magnetic films with Dzyaloshinskii–Moriya interaction (DMI) can host, together with axisymmetric skyrmions, other locally stable configurations even with the same topological charge. Among them are so-called tailed skyrmions Kuchkin et al.. They have an elongated shape and can exist in a narrow range of fields near the transition from spin spirals to a uniform ferromagnetic state. "Growing a tail" is an additional mechanism for obtaining new solitons. There is a continuous transition (homotopy) between such structures and usual skyrmions. The homotopies can be efficiently found by calculating MEPs using the geodesic nudged elastic band method [17]. The discovery of tailed skyrmions extends the range of already known soliton solutions.

Additional possibilities appear in multilayer systems due to controlled modification of the interlayer exchange coupling (IEC). For example, synthetic antiferromagnet can be obtained by establishing an antiferromagnetic (AFM) IEC between the ferromagnetic (FM) layers through a non-magnetic spacer. DMI-stabilized ferromagnetic skyrmions in each layer can couple with each other in these systems thus forming composite AFM skyrmions [21]. AFM skyrmions can also be created intrinsically in AFM materials. Ab initio calculations predict that this can be done, for example, by depositing a row-wise AFM Cr layer on the PdFeIr(111) structure hosting FM skyrmions [22]. In this case, only exchange interactions may be required to form a complex AF structure. Aldarawsheh et al. investigate this system using the Heisenberg model, which includes basic magnetic interactions necessary to form AFM skyrmions on a triangular lattice. Interestingly, deposited Cr layer does not introduce additional DMI interaction but leads to long-range exchange interaction involving several neighbor shells.

In three-dimensional magnets, the possibility of forming even more exotic topological structures can be realized. In cubic magnets with competing magnetic interactions, hopfions can be stabilized even in the absence of DMI. However, theoretical estimates show that they are stable only at low temperatures of a few kelvins [23, 24]. In the presence of DMI and an external magnetic field, hopfions embedded in a conical magnetic structure form heliknotons. Their experimental observation, however, is a challenging task. Additional challenge lies in the interpretation of experimental data, which is far from being unambiguous, especially in three-dimensional systems. Therefore, it is necessary to use mutually complementary techniques and explore different interpretation options. Savchenko et al. show this using magnetic bubbles with alternating chirality in domain walls as an example. There, mathematical modeling of the system response, obtained in the framework of different experimental methods in combination with various theoretical approaches to the study of dynamics and stability assessment, is very useful. Kuchkin et al. discuss the stability of heliknotons and conditions of their detection based on micromagnetic modeling, rate theory, and stochastic spin dynamics simulations.

In three-dimensional samples with chiral interactions, delocalized states are possible in addition to localized topological structures. Leonov and Pappas carried out a systematic study of the states of an inclined spiral arising due to competition of cubic and exchange anisotropies inherent to cubic helimagnets. Field-controlled reorientation of metastable skyrmion lattices caused by competing anisotropies, may be responsible for some features in the experimental phase diagrams of Cu_2OSeO_3.

Author contributions

VU: Writing–original draft, Writing–review and editing. DT: Writing–original draft, Writing–review and editing. BG: Writing–original draft, Writing–review and editing. PB: Writing–original draft, Writing–review and editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

1. Göbel B, Mertig I, Tretiakov OA. Beyond skyrmions: Review and perspectives of alternative magnetic quasiparticles. *Phys Rep* (2021) 895:1–28. doi:10.1016/j.physrep.2020.10.001

2. Brown WF. Thermal fluctuations of a single-domain particle. *Phys Rev* (1963) 130:1677–86. doi:10.1103/PhysRev.130.1677

3. Brown WF. Thermal fluctuation of fine ferromagnetic particles. *IEEE Trans Magn* (1979) 15:1196–208. doi:10.1109/TMAG.1979.1060329

4. Wild J, Meier TNG, Pöllath S, Kronseder M, Bauer A, Chacon A, et al. Entropy-limited topological protection of skyrmions. *Sci Adv* (2017) 3:e1701704. doi:10.1126/sciadv.1701704

5. Hagemeister J, Romming N, von Bergmann K, Vedmedenko EY, Wiesendanger R. Stability of single skyrmionic bits. *Nat Commun* (2015) 6:8455. doi:10.1038/ncomms9455

6. Bessarab PF, Uzdin VM, Jónsson H. Harmonic transition-state theory of thermal spin transitions. *Phys Rev B* (2012) 85:184409. doi:10.1103/PhysRevB.85.184409

7. Fiedler G, Fidler J, Lee J, Schrefl T, Stamps RL, Braun HB, et al. Direct calculation of the attempt frequency of magnetic structures using the finite element method. *J Appl Phys* (2012) 111:093917. doi:10.1063/1.4712033

8. Vogler C, Bruckner F, Bergmair B, Huber T, Suess D, Dellago C. Simulating rare switching events of magnetic nanostructures with forward flux sampling. *Phys Rev B* (2013) 88:134409. doi:10.1103/PhysRevB.88.134409

9. Lobanov IS, Potkina MN, Uzdin VM. Stability and lifetimes of magnetic states of nano- and microstructures (brief review). *JETP Lett* (2021) 113:801–13. doi:10.1134/S0021364021120109

10. Lobanov IS, Jónsson H, Uzdin VM. Mechanism and activation energy of magnetic skyrmion annihilation obtained from minimum energy path calculations. *Phys Rev B* (2016) 94:174418. doi:10.1103/PhysRevB.94.174418

11. Bessarab PF, Müller GP, Lobanov IS, Rybakov FN, Kiselev NS, Jónsson H, et al. Lifetime of racetrack skyrmions. *Sci Rep* (2018) 8:3433. doi:10.1038/s41598-018-21623-3

12. Desplat L, Kim JV, Stamps RL. Paths to annihilation of first- and second-order (anti)skyrmions via (anti)meron nucleation on the frustrated square lattice. *Phys Rev B* (2019) 99:174409. doi:10.1103/PhysRevB.99.174409

13. Muckel F, von Malottki S, Holl C, Pestka B, Pratzer M, Bessarab PF, et al. Experimental identification of two distinct skyrmion collapse mechanisms. *Nat Phys* (2021) 17:395–402. doi:10.1038/s41567-020-01101-2

14. Desplat L, Suess D, Kim JV, Stamps RL. Thermal stability of metastable magnetic skyrmions: Entropic narrowing and significance of internal eigenmodes. *Phys Rev B* (2018) 98:134407. doi:10.1103/PhysRevB.98.134407

15. von Malottki S, Bessarab PF, Haldar S, Delin A, Heinze S. Skyrmion lifetime in ultrathin films. *Phys Rev B* (2019) 99:060409. doi:10.1103/PhysRevB.99.060409

16. Varentcova AS, von Malottki S, Potkina MN, Kwiatkowski G, Heinze S, Bessarab PF. Toward room-temperature nanoscale skyrmions in ultrathin films. *NPJ Comput Mater* (2020) 6:193. doi:10.1038/s41524-020-00453-w

17. Bessarab PF, Uzdin VM, Jónsson H. Method for finding mechanism and activation energy of magnetic transitions, applied to skyrmion and antivortex annihilation. *Comput Phys Commun* (2015) 196:335–47. doi:10.1016/j.cpc.2015.07.001

18. Desplat L, Vogler C, Kim JV, Stamps RL, Suess D. Path sampling for lifetimes of metastable magnetic skyrmions and direct comparison with Kramers' method. *Phys Rev B* (2020) 101:060403. doi:10.1103/PhysRevB.101.060403

19. Lobanov IS, Uzdin VM. The lifetime of micron scale topological chiral magnetic states with atomic resolution. *Comput Phys Commun* (2021) 269:108136. doi:10.1016/j.cpc.2021.108136

20. Potkina MN, Lobanov IS, Jónsson H, Uzdin VM. Stability of magnetic skyrmions: Systematic calculations of the effect of size from nanometer scale to microns. *Phys Rev B* (2023) 107:184414. doi:10.1103/PhysRevB.107.184414

21. Voronin KV, Lobanov IS, Uzdin VM. Activation energy and mechanisms for skyrmion collapse in synthetic antiferromagnets. *JETP Lett* (2022) 116:240–5. doi:10.1134/S0021364022601361

22. Aldarawsheh A, Fernandes IL, Brinker S, Sallermann M, Abusaa M, Blügel S, et al. Emergence of zero-field non-synthetic single and interchained antiferromagnetic skyrmions in thin films. *Nat Commun* (2022) 13:7369. doi:10.1038/s41467-022-35102-x

23. Sallermann M, Jónsson H, Blügel S. Stability of hopfions in bulk magnets with competing exchange interactions. *Phys Rev B* (2023) 107:104404. doi:10.1103/PhysRevB.107.104404

24. Lobanov IS, Uzdin VM. Lifetime, collapse, and escape paths for hopfions in bulk magnets with competing exchange interactions. *Phys Rev B* (2023) 107:104405. doi:10.1103/PhysRevB.107.104405